Deformation and fracture of metal foams : Experiments and simulations

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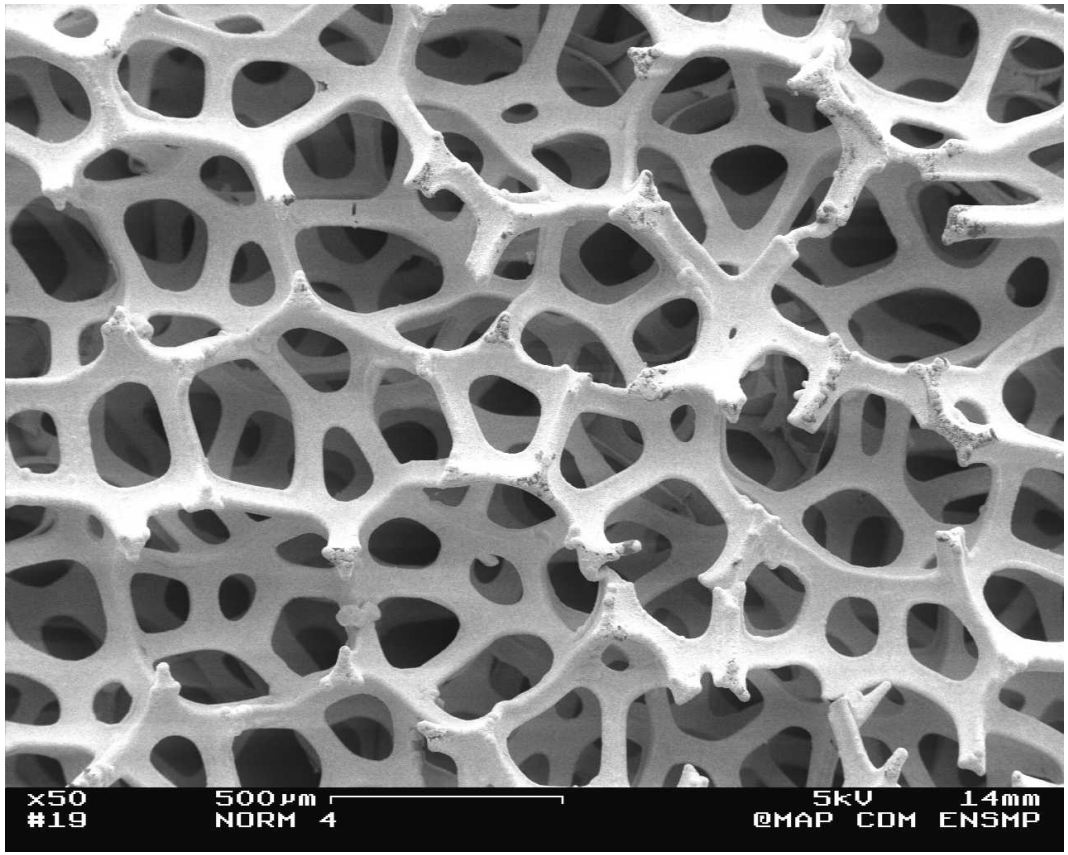
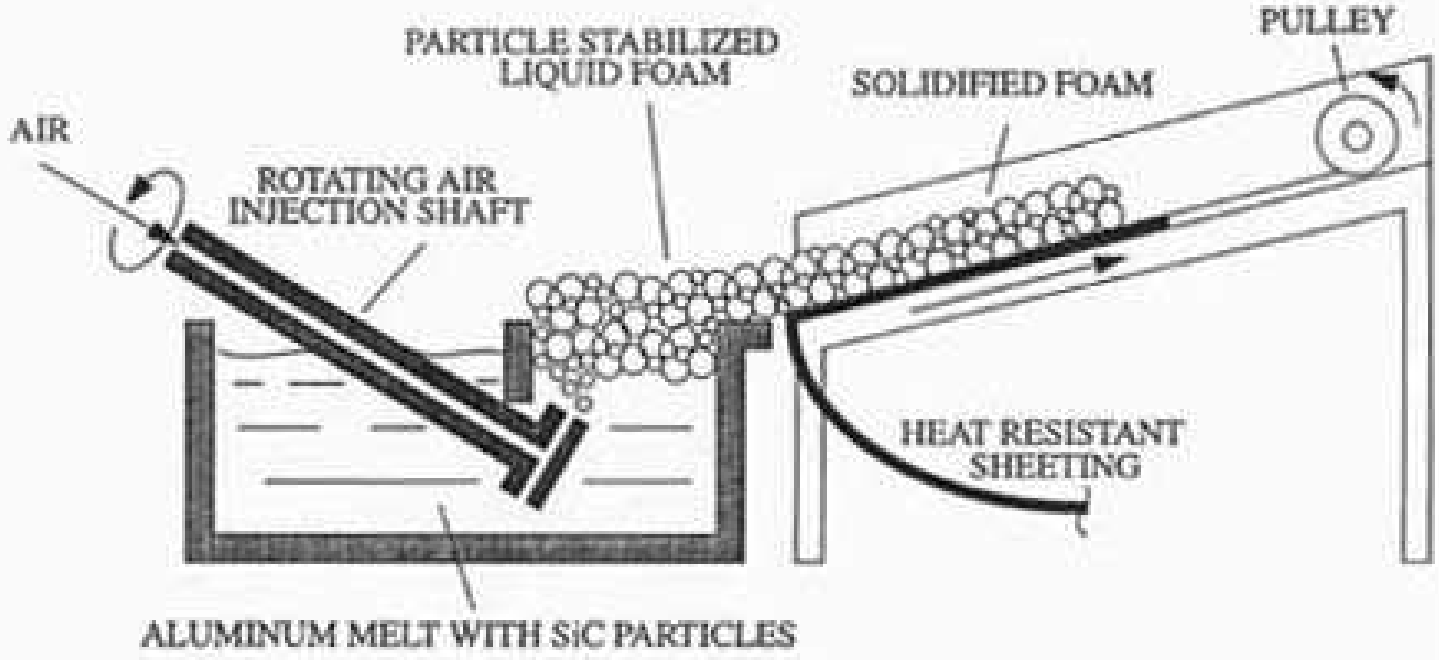
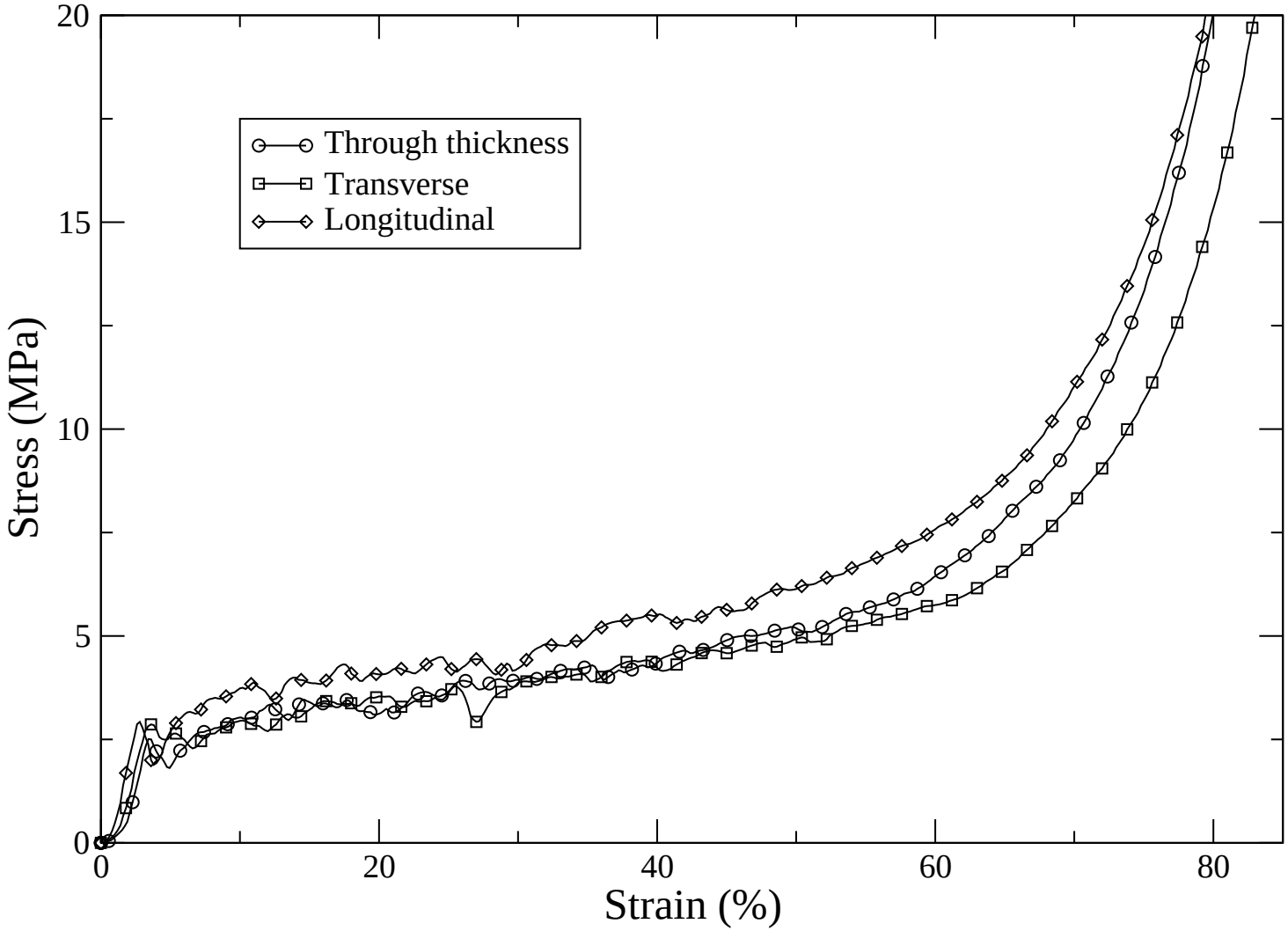
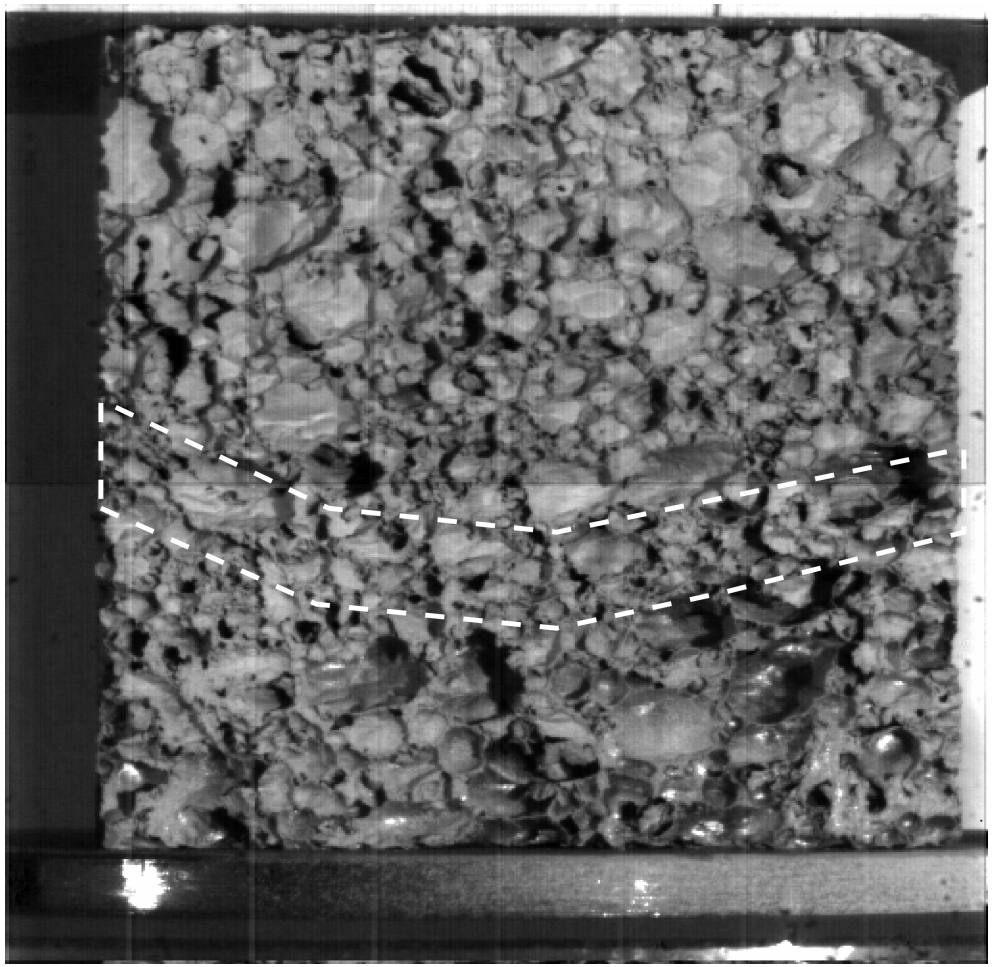
Aluminium and Nickel Foams

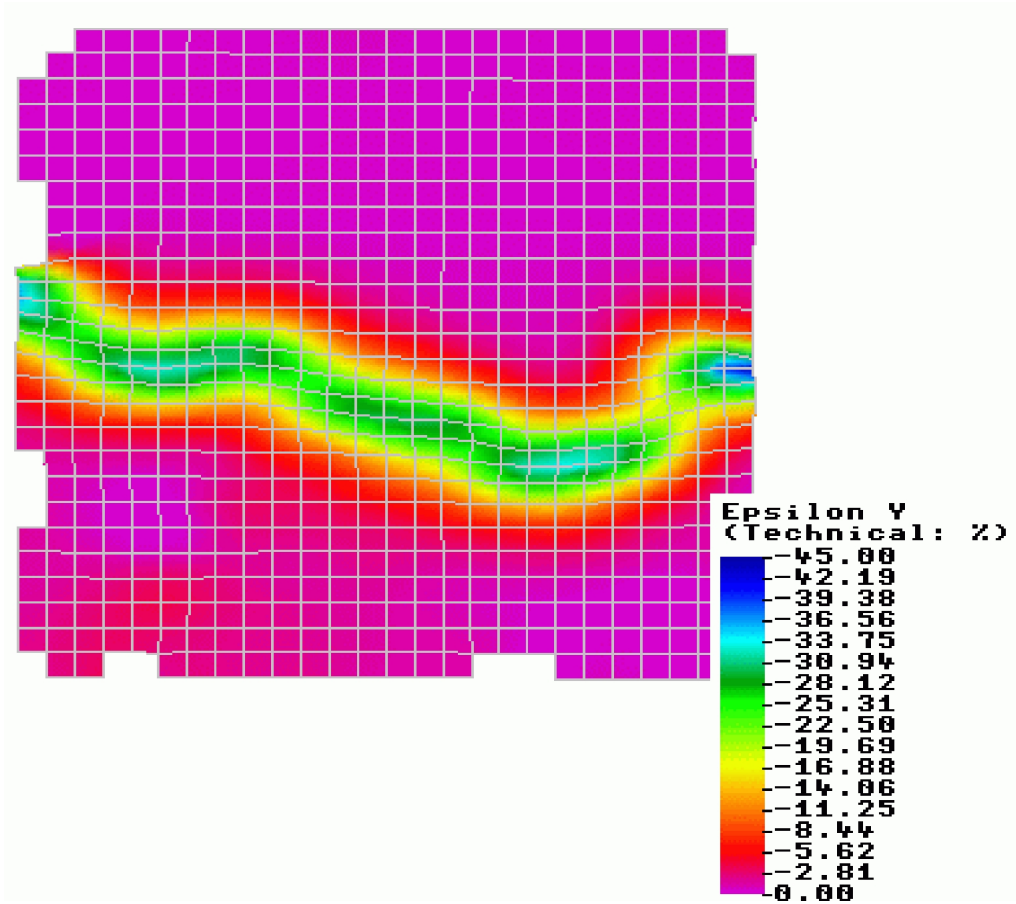


Alcan Al/SiC Foam Production




Through thickness
Transverse
Longitudinal
Stress (MPa)
Strain (%)
0
5
10
15
20
0
20
40
60
80




Epsilon Y
(Technical: %)
-45.00
-42.19
-39.38
-36.56
-33.75
-30.94
-28.12
-25.31
-22.50
-19.69
-16.88
-14.06
-11.25
-8.44
-5.62
-2.81
0.00

Continuum plasticity model for foams

elliptic criterion : $f(\underset{\sim}{\boldsymbol{\sigma}}) = \sqrt{\frac{3}{2}C\,\underset{\sim}{\boldsymbol{s}} : \underset{\sim}{\boldsymbol{s}} + F\,(trace\ \underset{\sim}{\boldsymbol{\sigma}})^2} - R(p)$ (cf. powder metallurgy)

normality rule :

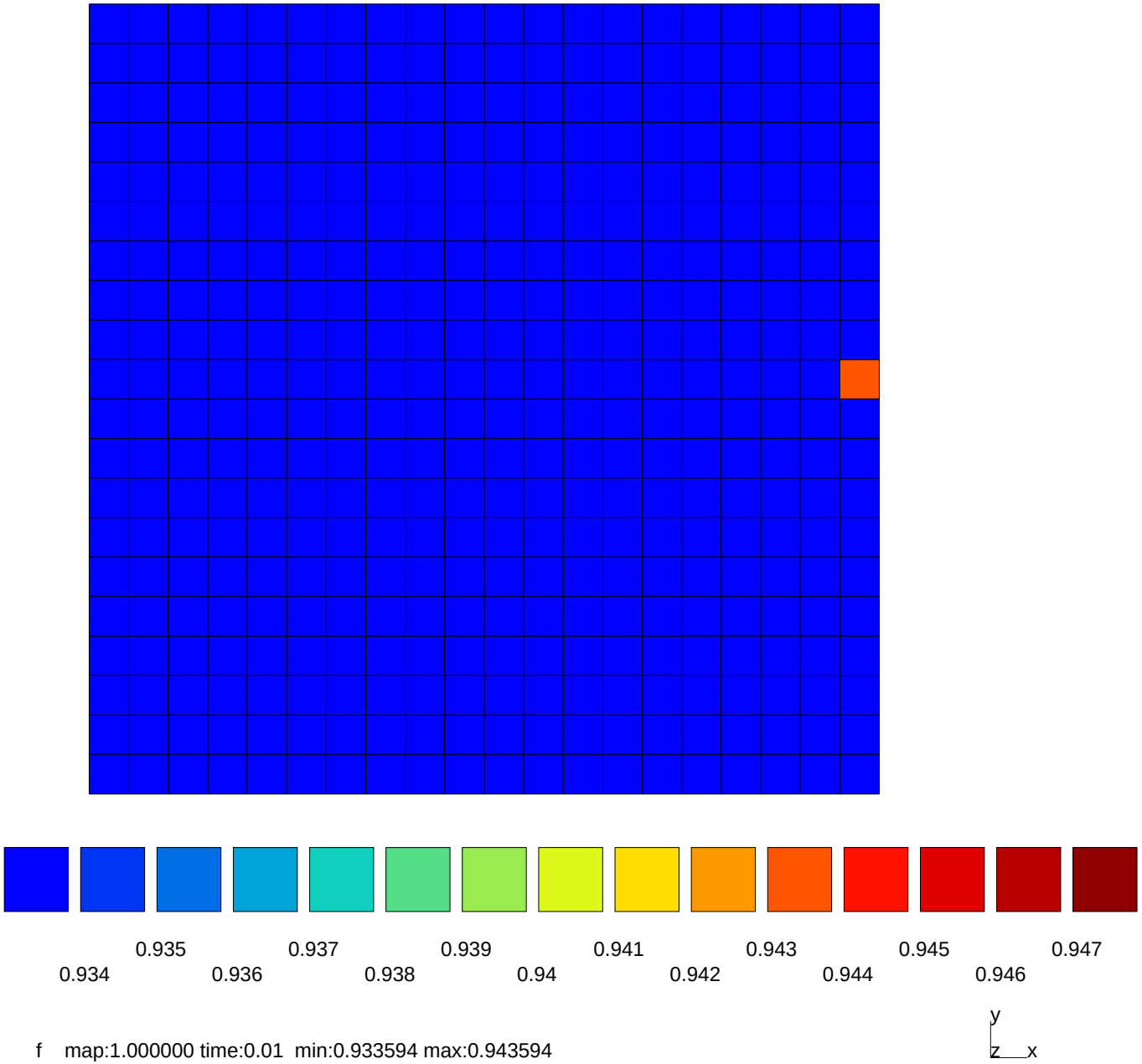
$$\underset{\sim}{\dot{\boldsymbol{\varepsilon}}}^p = \dot{p}\frac{\partial f}{\partial \underset{\sim}{\boldsymbol{\sigma}}} = \dot{p}\frac{\frac{3}{2}C\underset{\sim}{\boldsymbol{s}} + F\mathrm{Trace}\,\underset{\sim}{\boldsymbol{\sigma}}\ \underset{\sim}{\mathbf{1}}}{\hat{\sigma}}$$

$$\hat{\sigma} = \sqrt{\frac{3}{2}C\,\underset{\sim}{\boldsymbol{s}} : \underset{\sim}{\boldsymbol{s}} + F\,(trace\ \underset{\sim}{\boldsymbol{\sigma}})^2}$$

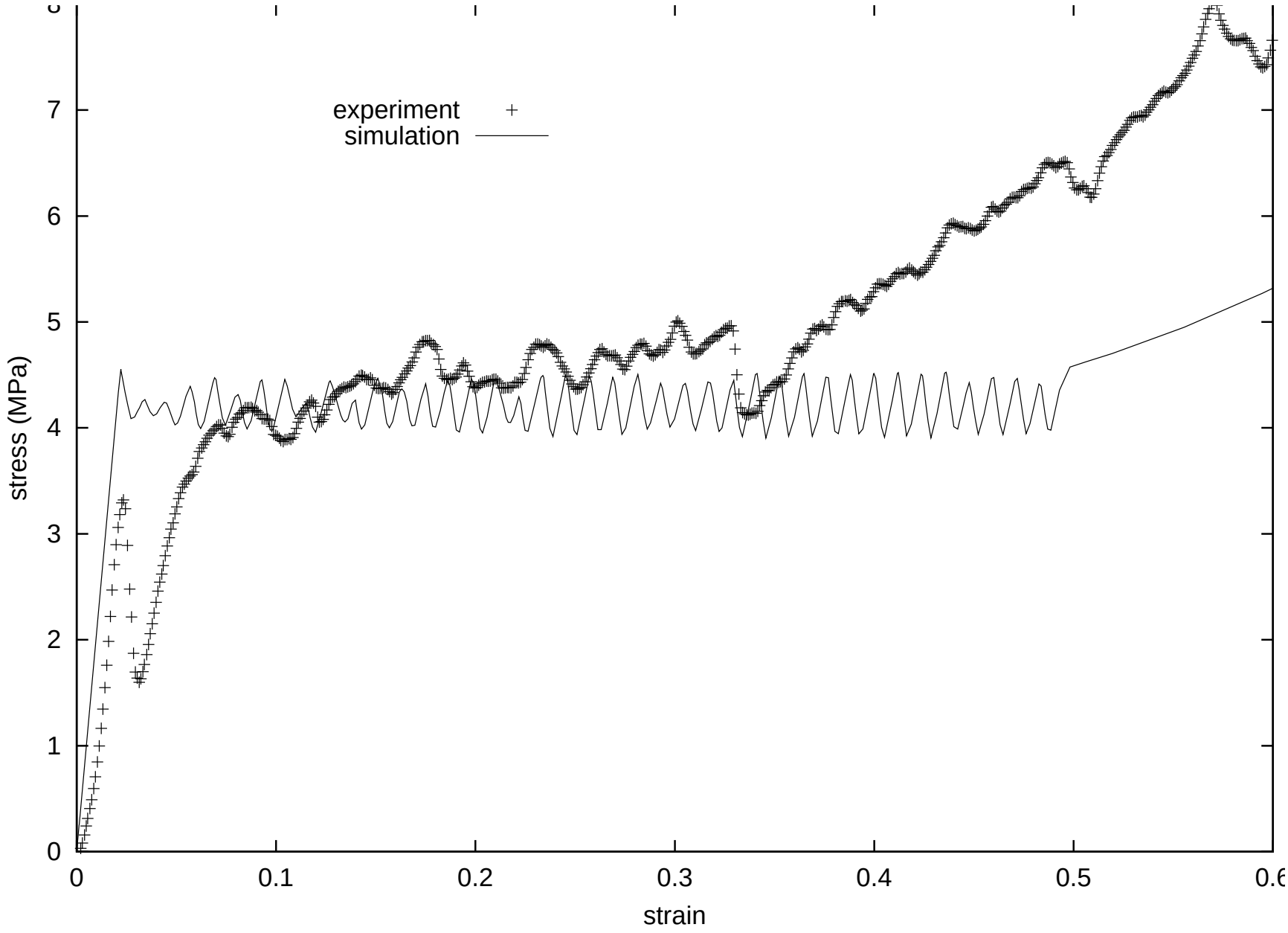
plastic multiplier : $\dot{p} = \sqrt{\frac{2}{3C}\underset{\sim}{\dot{\boldsymbol{e}}}^p : \underset{\sim}{\dot{\boldsymbol{e}}}^p + \frac{1}{9F}trace(\underset{\sim}{\dot{\boldsymbol{\varepsilon}}}^p)^2}$

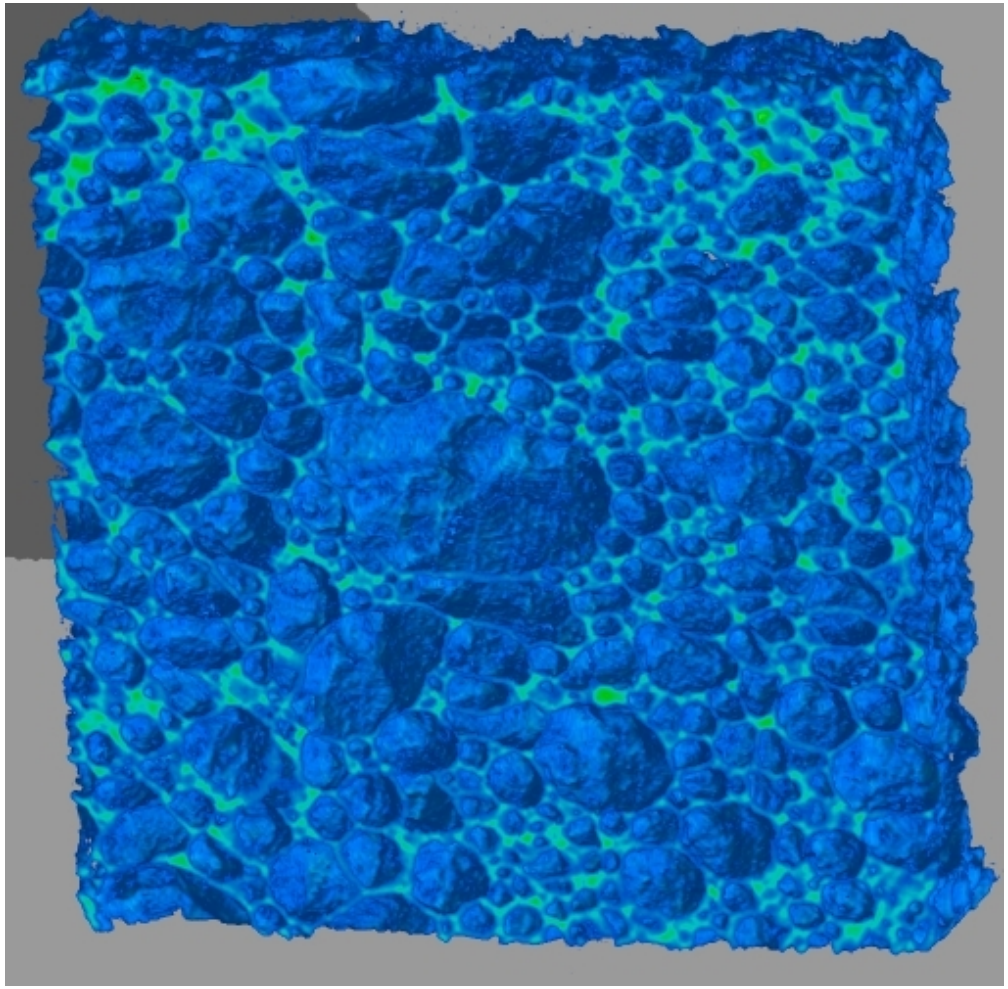
lateral contraction :

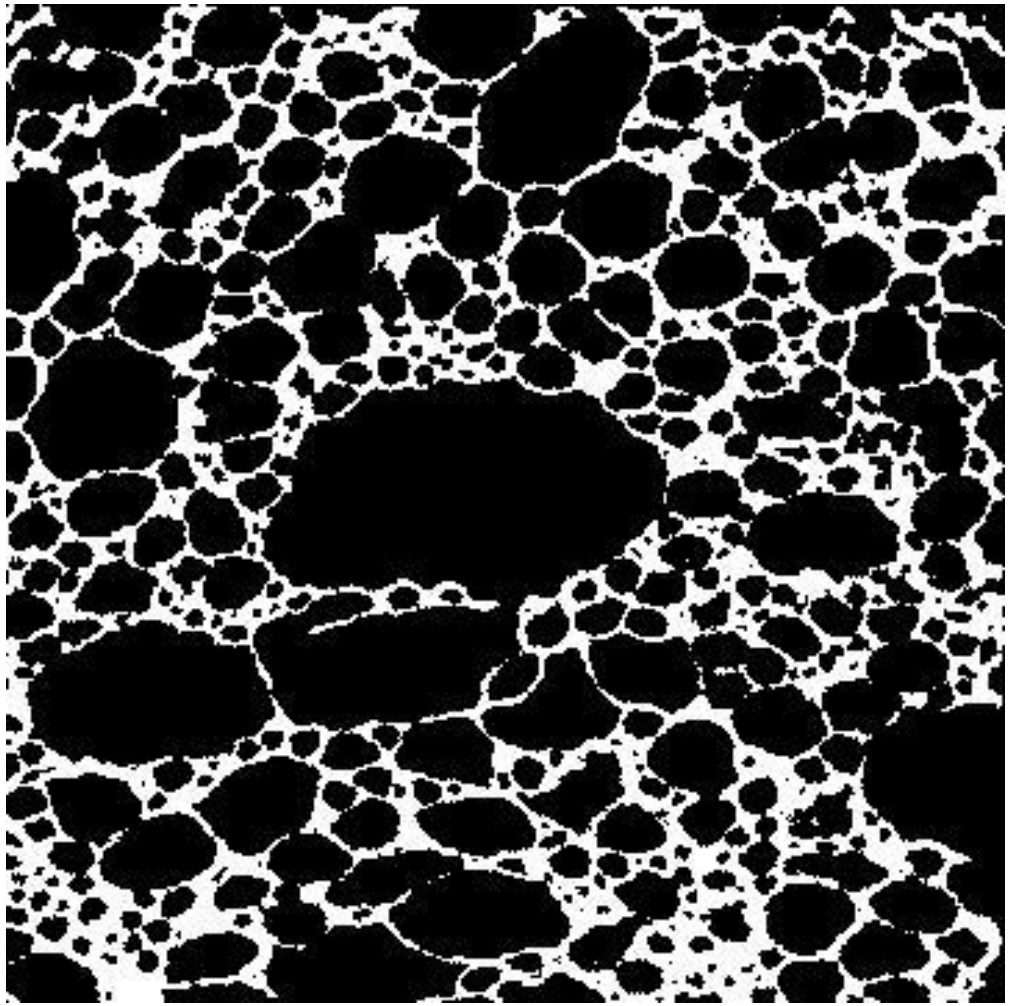
$$\nu_p = \frac{C/2 - F}{C + F}$$

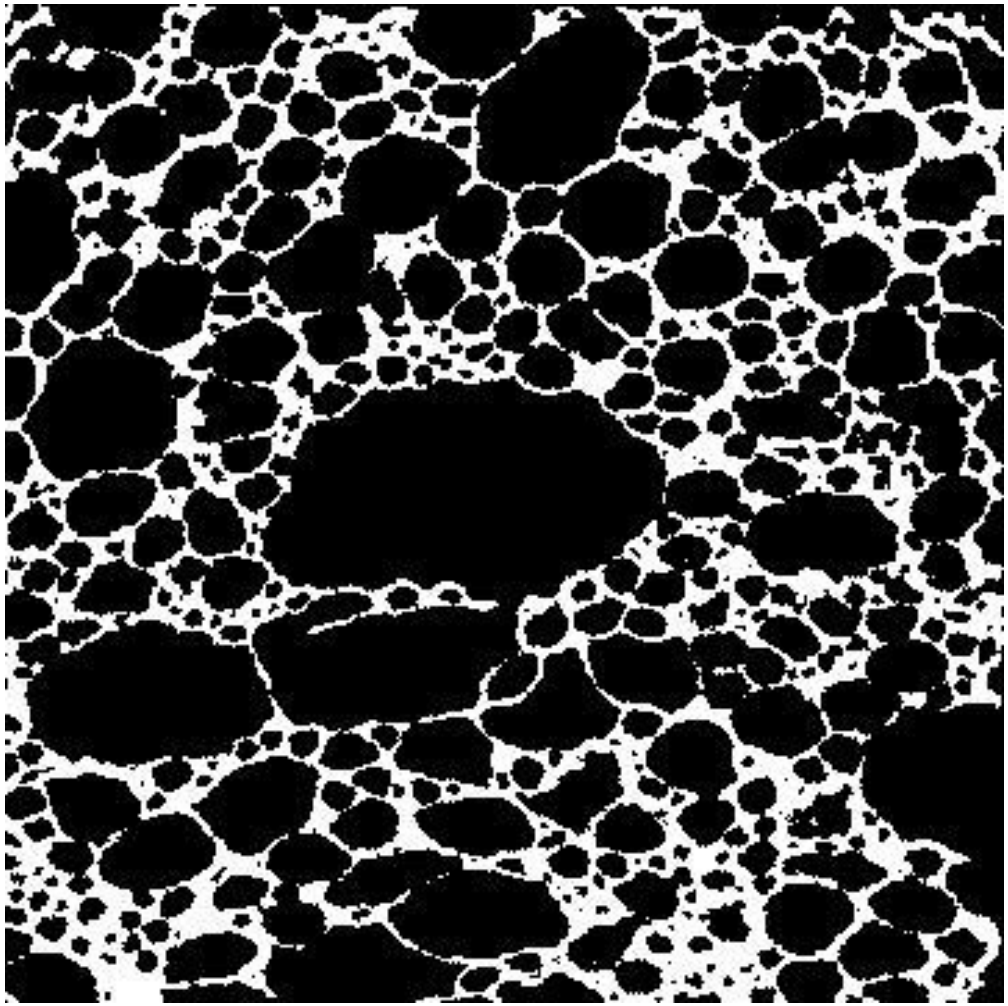


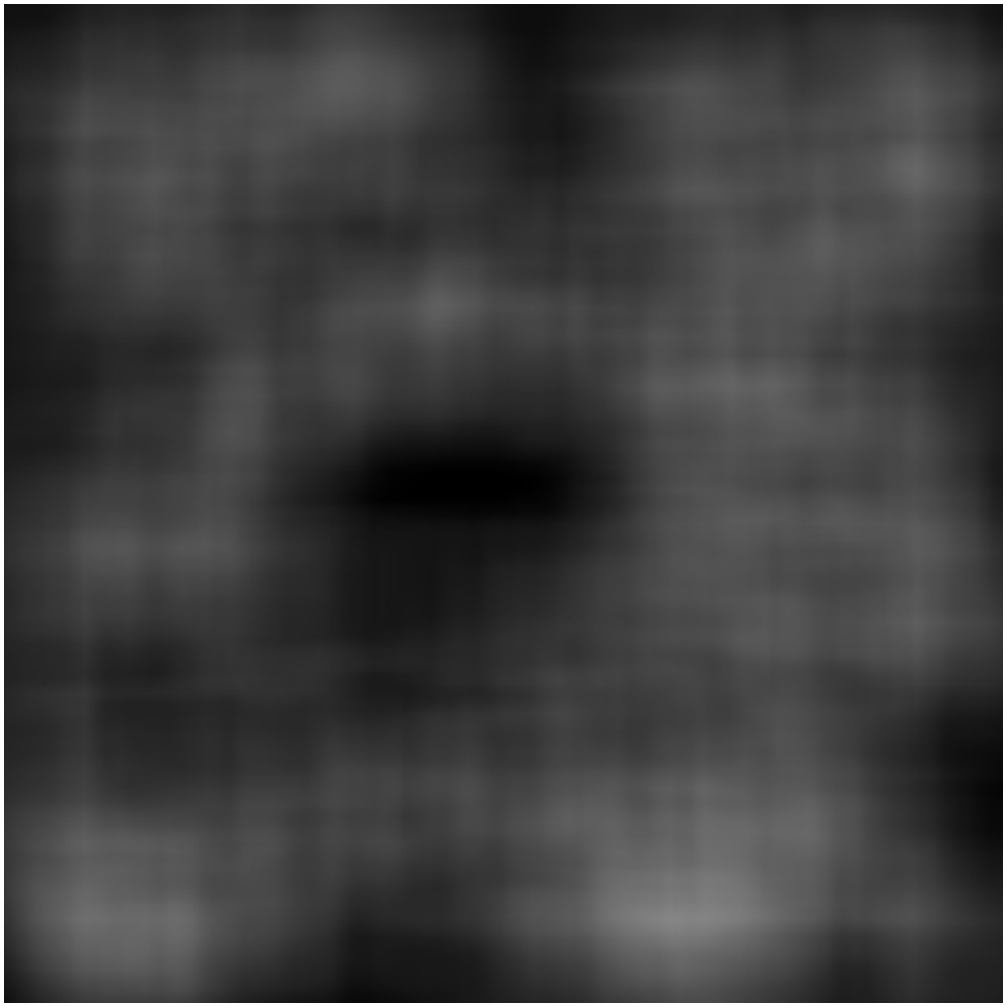
f map:1.000000 time:0.01 min:0.933594 max:0.943594

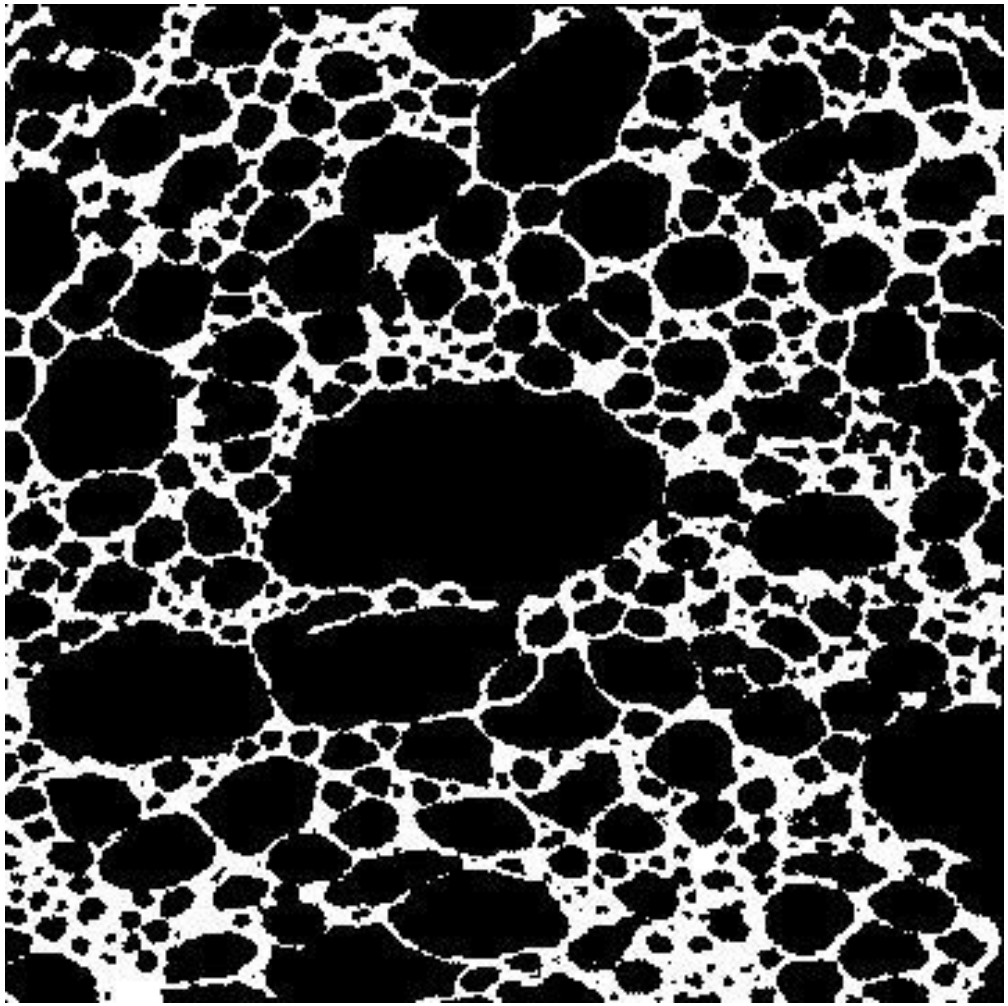

experiment
simulation
stress (MPa)
strain
0
1
2
3
4
5
6
7
8
0
0.1
0.2
0.3
0.4
0.5
0.6

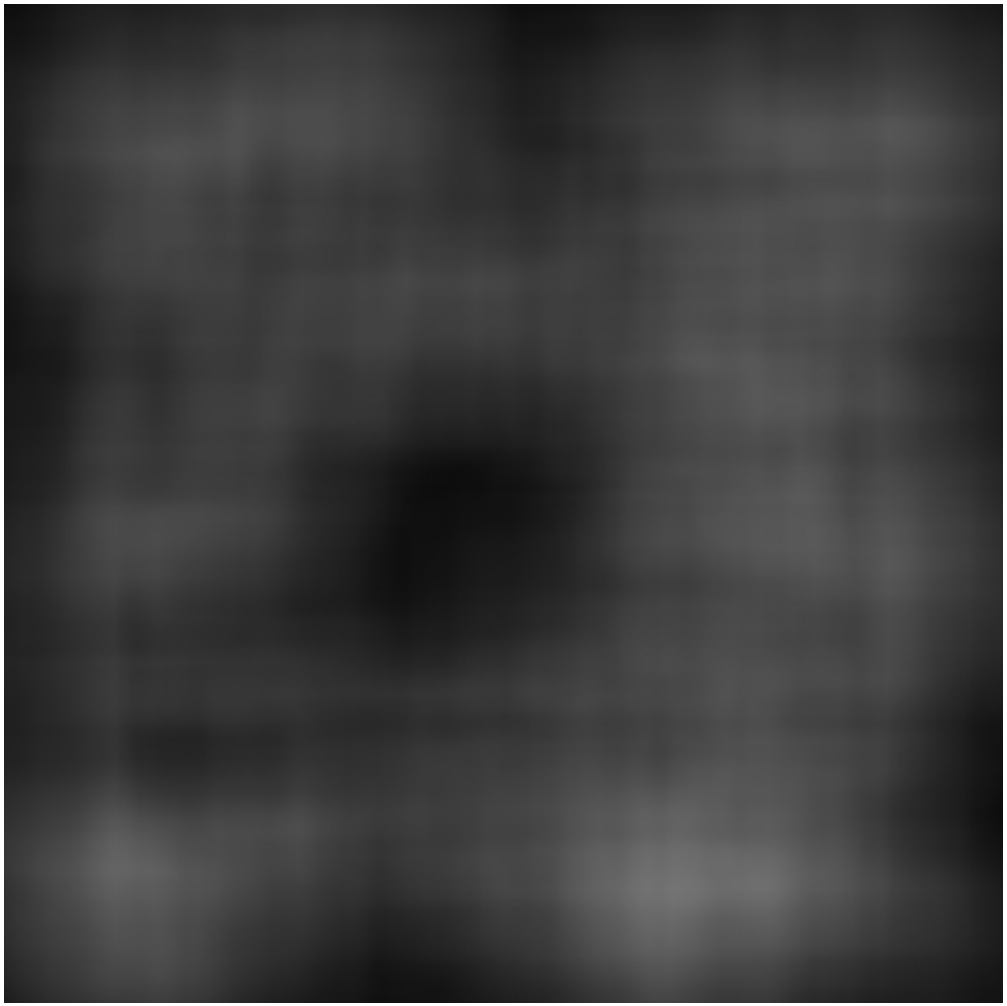


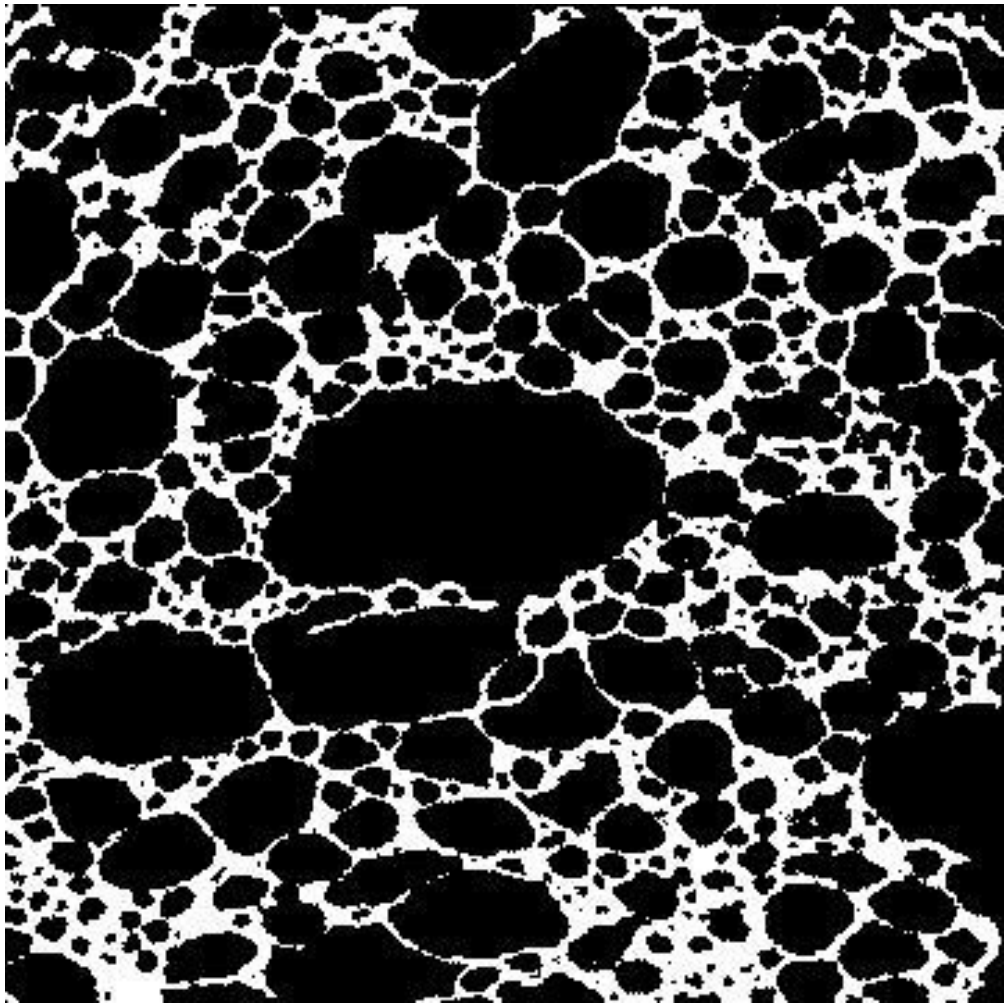


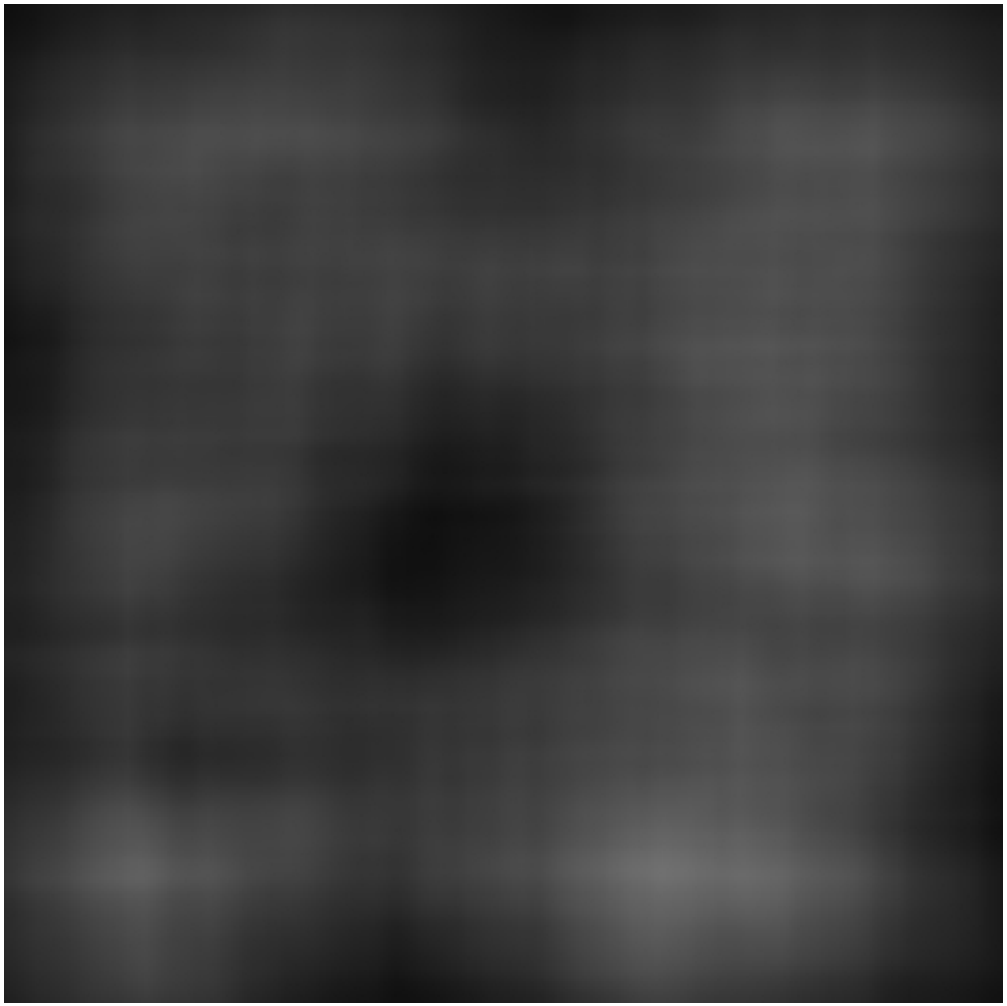


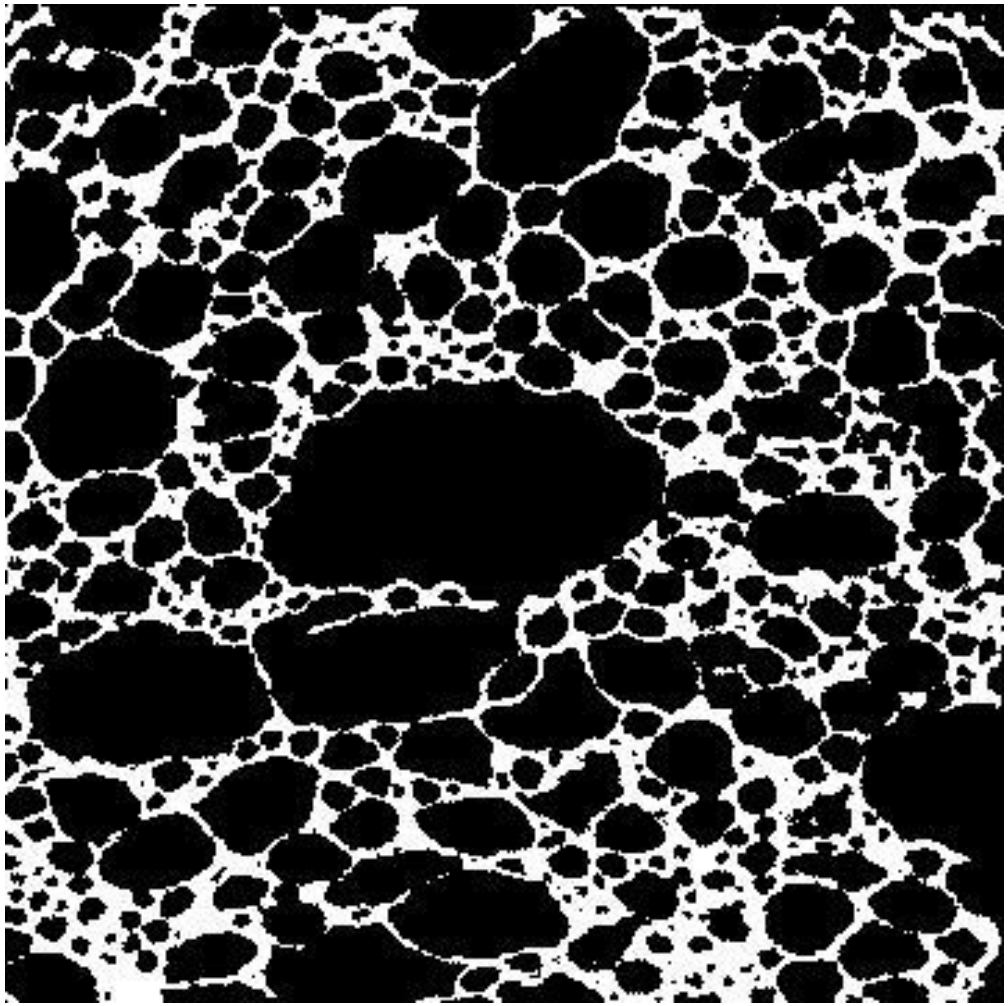


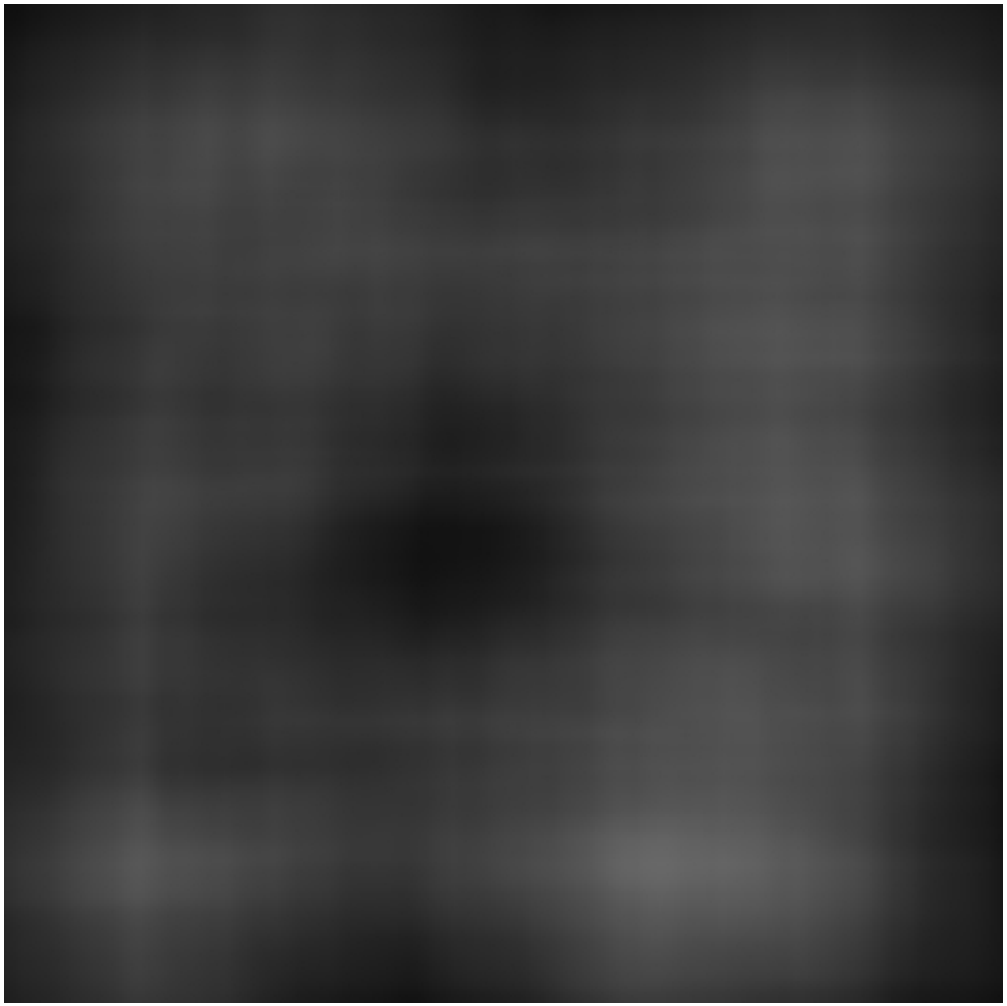


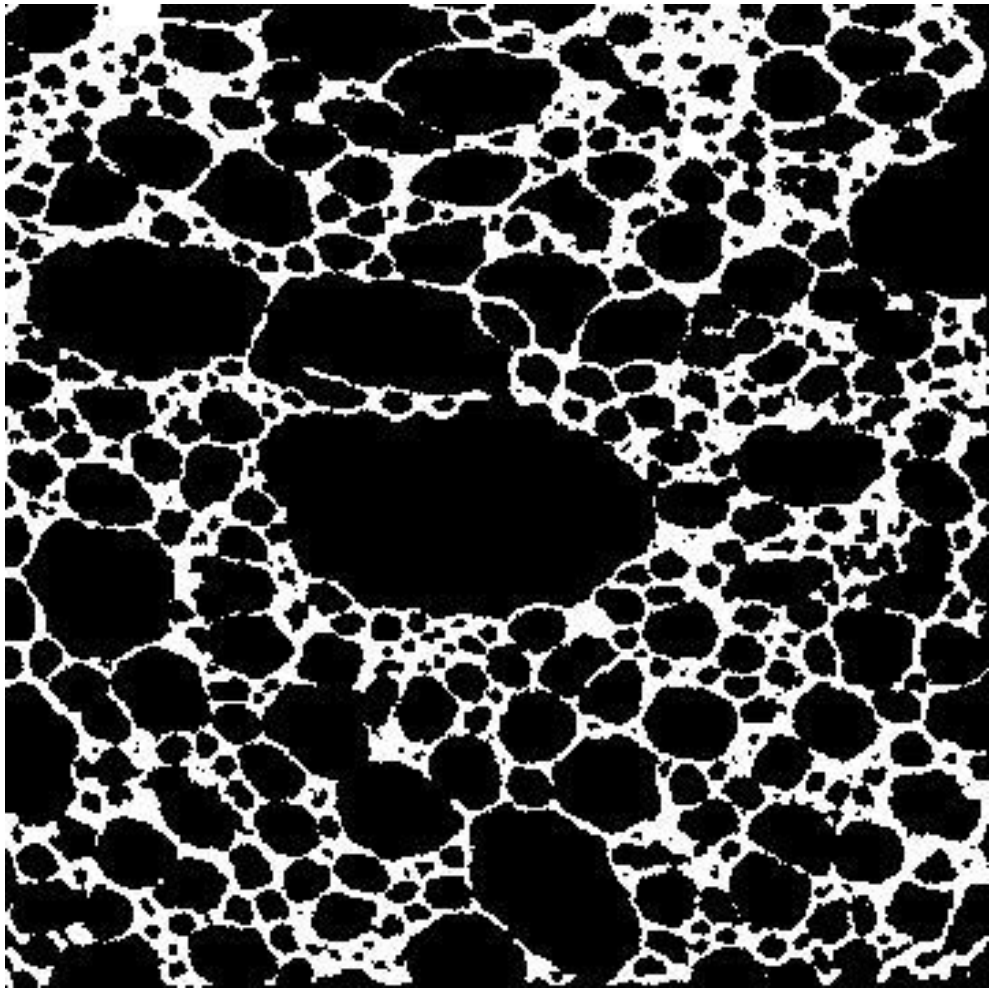


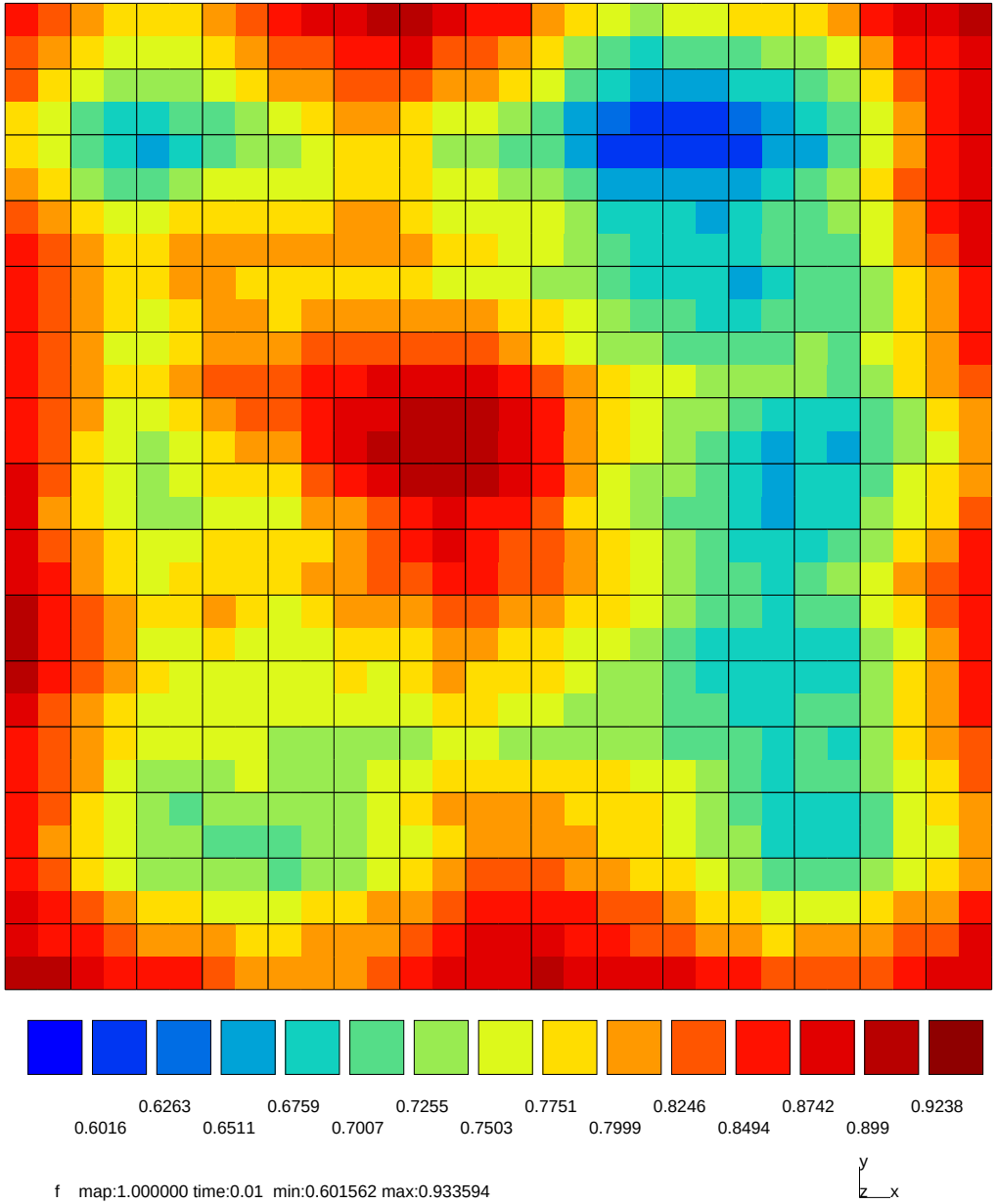


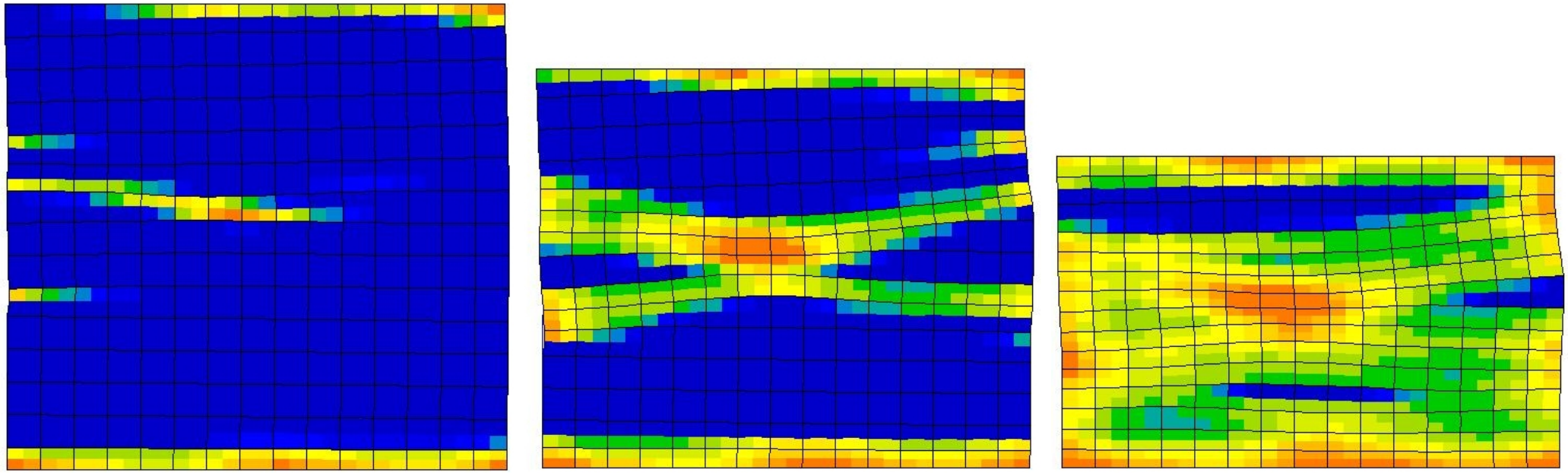


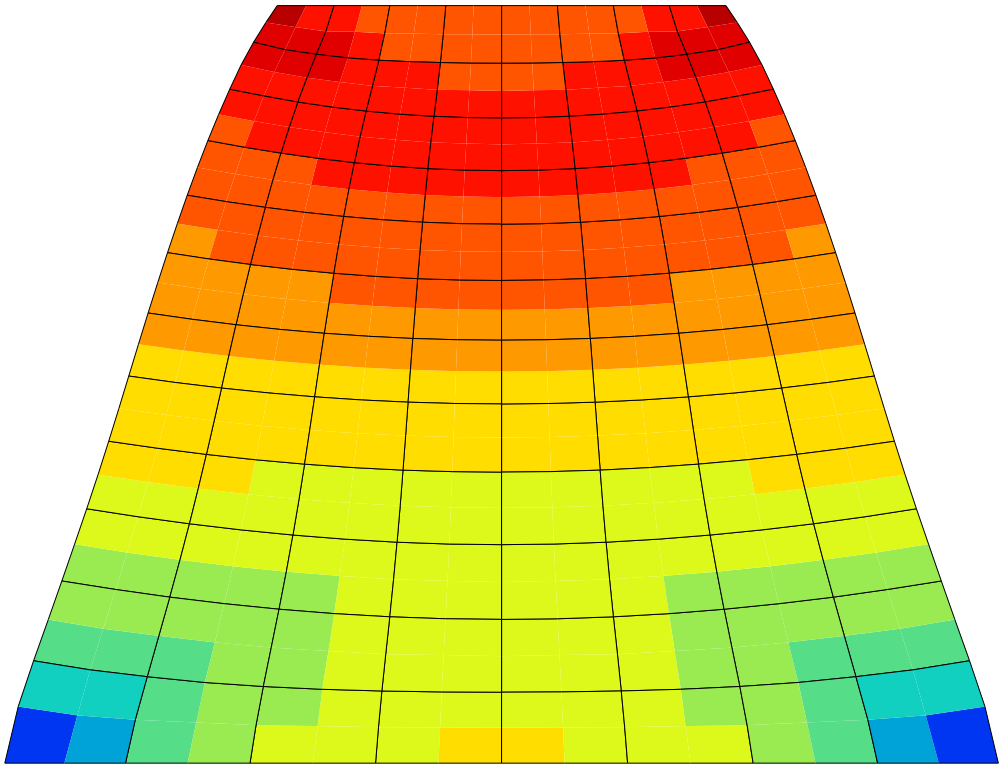


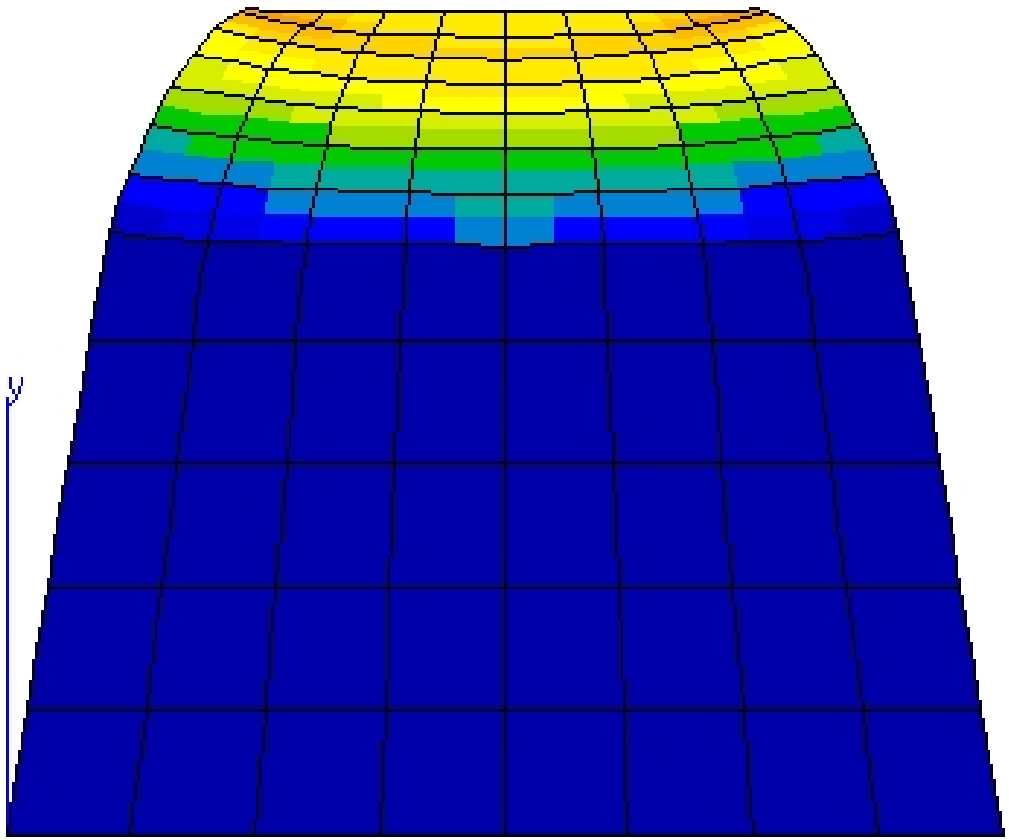




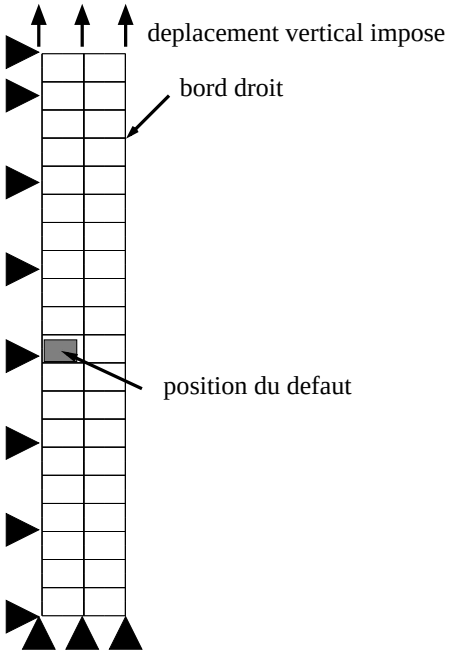

0.6016
0.6263
0.6511
0.6759
0.7007
0.7255
0.7503
0.7751
0.7999
0.8246
0.8494
0.8742
0.899
0.9238
f map:1.000000 time:0.01 min:0.601562 max:0.933594
y
z
x

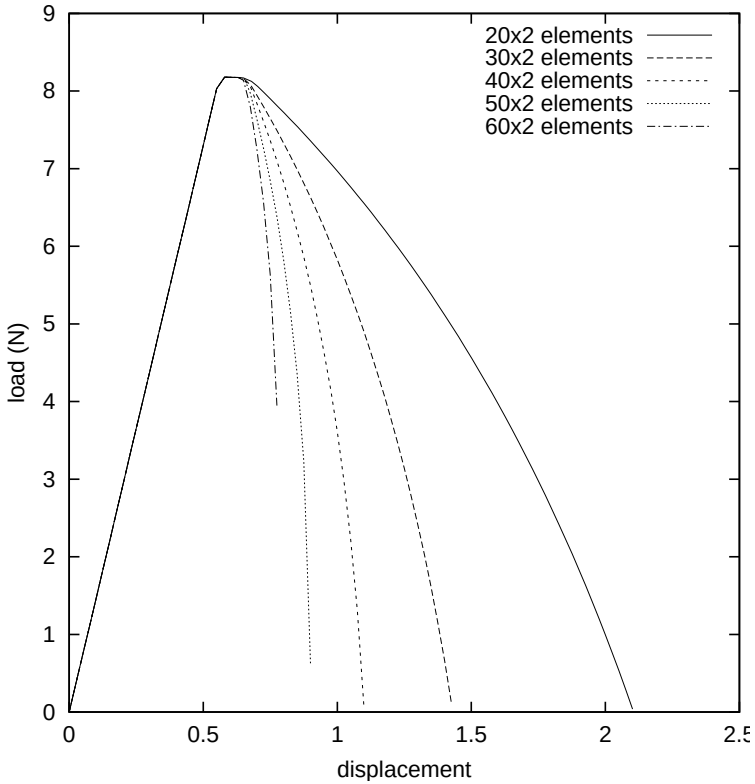


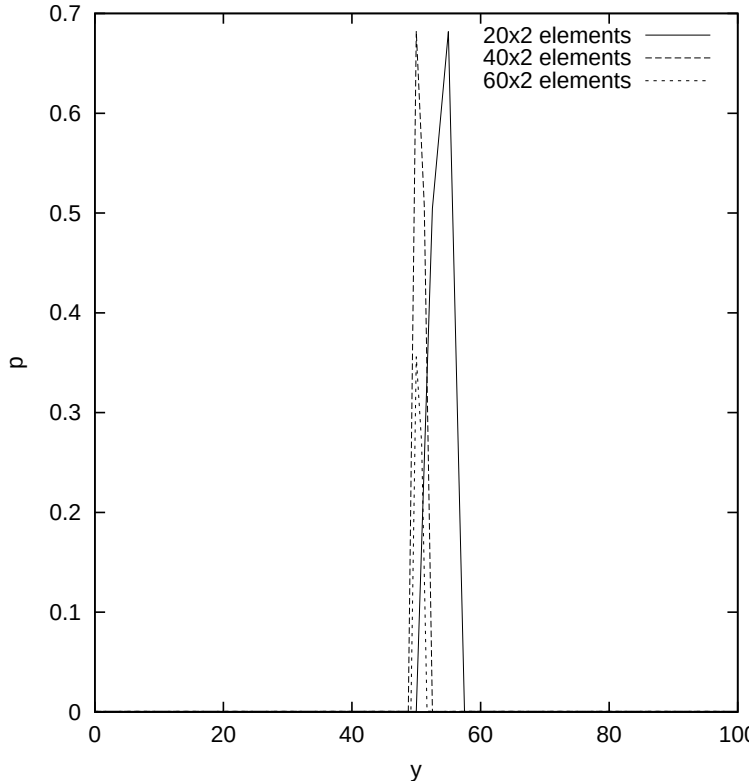



y

Mesh dependence for localization band formation







Metal foam as a micromorphic continuum : The *microfoam* model

Degrees of freedom at material point

$$\text{displacement vector } \underline{\boldsymbol{u}}\,, \quad \text{microdeformation tensor } \underset{\sim}{\boldsymbol{\chi}}$$

the microdeformation field is generally not compatible [Mindlin, 1964] [Eringen, 1964]

Deformation measures

$$\text{strain tensor} \quad \underset{\sim}{\boldsymbol{\varepsilon}} = (\underline{\boldsymbol{u}} \otimes \boldsymbol{\nabla} + \boldsymbol{\nabla} \otimes \underline{\boldsymbol{u}}\,)/2$$

$$\text{relative deformation tensor} \quad \underset{\sim}{\boldsymbol{e}} = \underline{\boldsymbol{u}} \otimes \boldsymbol{\nabla} - \underset{\sim}{\boldsymbol{\chi}}$$

$$\text{microdeformation gradient} \quad \underset{\sim}{\boldsymbol{K}} = \underset{\sim}{\boldsymbol{\chi}} \otimes \boldsymbol{\nabla}$$

Power density of internal forces / generalized stress tensors

$$p^{(i)} = \underset{\sim}{\boldsymbol{\sigma}} : \dot{\underset{\sim}{\boldsymbol{\varepsilon}}} + \underset{\sim}{\boldsymbol{s}} : \dot{\underset{\sim}{\boldsymbol{e}}} + \underset{\sim}{\boldsymbol{M}} \vdots \dot{\underset{\sim}{\boldsymbol{K}}}$$

Balance of momentum

$$(\underset{\sim}{\boldsymbol{\sigma}} + \underset{\sim}{\boldsymbol{s}}).\boldsymbol{\nabla} = 0$$

Balance of micromorphic momentum

$$\underset{\approx}{\boldsymbol{M}}.\boldsymbol{\nabla} + \underset{\sim}{\boldsymbol{s}} = 0$$

Boundary conditions (traction and double traction vectors)

$$\underline{\boldsymbol{t}} = (\underset{\sim}{\boldsymbol{\sigma}} + \underset{\sim}{\boldsymbol{s}}).\underline{\boldsymbol{n}}\,, \quad \underset{\sim}{\boldsymbol{T}} = \underset{\approx}{\boldsymbol{M}}.\underline{\boldsymbol{n}}$$

Variational formulation for finite element implementation

$$\int_V p^{(i)}\, dV = \int_{\partial V} \left(\underline{\boldsymbol{t}}\,.\dot{\underline{\boldsymbol{n}}} + \underset{\sim}{\boldsymbol{T}} : \dot{\underset{\sim}{\boldsymbol{\chi}}} \right)\, dS$$

The *microfoam* model : Constitutive equations

Strain partition

$$\underset{\sim}{\boldsymbol{\varepsilon}} = \underset{\sim}{\boldsymbol{\varepsilon}}^e + \underset{\sim}{\boldsymbol{\varepsilon}}^p, \quad \underset{\sim}{\boldsymbol{e}} = \underset{\sim}{\boldsymbol{e}}^e + \underset{\sim}{\boldsymbol{e}}^p, \quad \underset{\approx}{\boldsymbol{K}} = \underset{\approx}{\boldsymbol{K}}^e + \underset{\approx}{\boldsymbol{K}}^p$$

Linear elasticity

$$\underset{\sim}{\boldsymbol{\sigma}} = \underset{\approx}{\boldsymbol{c}} : \underset{\sim}{\boldsymbol{\varepsilon}}^e, \quad \underset{\sim}{\boldsymbol{s}} = \underset{\approx}{\boldsymbol{a}} : \underset{\sim}{\boldsymbol{e}}^e, \quad \underset{\approx}{\boldsymbol{M}} = \underset{\approx\approx}{\boldsymbol{A}} \vdots \underset{\approx}{\boldsymbol{K}}^e$$

simplified moduli as proposed by [Shu et al., 1999] $\underset{\approx}{\boldsymbol{M}} = l_c^2 \underset{\approx}{\boldsymbol{c}} : \underset{\approx}{\boldsymbol{K}}^e$

characteristic length l_c

when $||\underset{\approx}{\boldsymbol{a}}||$ is very large, and if $\underset{\sim}{\boldsymbol{e}}^p = 0$, then $\underline{\boldsymbol{u}} \otimes \boldsymbol{\nabla} \simeq \underset{\sim}{\boldsymbol{\chi}}$ (second gradient theory)

Yield criterion

$$f(\underset{\sim}{\boldsymbol{\sigma}}) = \sigma_{eq} - R$$

$$\sigma_{eq} = \left(\frac{3}{2} C \underset{\sim}{\boldsymbol{\sigma}}^{\mathrm{dev}} : \underset{\approx}{\boldsymbol{H}} : \underset{\sim}{\boldsymbol{\sigma}}^{\mathrm{dev}} + F(\underset{\sim}{\boldsymbol{P}} : \underset{\sim}{\boldsymbol{\sigma}})^2 + a_1 \underset{\sim}{\boldsymbol{s}}^{\mathrm{dev}} : \underset{\sim}{\boldsymbol{s}}^{\mathrm{dev}} + a_2 \underset{\sim}{\boldsymbol{s}}^{\mathrm{dev}} : \underset{\sim}{\boldsymbol{s}}^{\mathrm{devT}} \right.$$

$$\left. + a_3 (\mathrm{Tr}\, \underset{\sim}{\boldsymbol{s}})^2 + b_1 \underset{\approx}{\boldsymbol{M}} \vdots \underset{\approx}{\boldsymbol{M}} \right)^{\frac{1}{2}}$$

Normality rule

$$\dot{\underset{\sim}{\boldsymbol{\varepsilon}}}^p = \dot{p} \frac{\partial f}{\partial \underset{\sim}{\boldsymbol{\sigma}}}, \quad \dot{\underset{\sim}{\boldsymbol{e}}}^p = \dot{p} \frac{\partial f}{\partial \underset{\sim}{\boldsymbol{s}}}, \quad \dot{\underset{\approx}{\boldsymbol{K}}}^p = \dot{p} \frac{\partial f}{\partial \underset{\approx}{\boldsymbol{M}}}$$

Microfoam 1 : $a_1 = a_2 = a_3 = b_1 = 0, ||\underset{\sim}{\boldsymbol{a}}||\mathrm{very\ large}$

constrained microdeformation (second gradient), linear relationship between gradient of microdeformation and hyperstress tensor

Finite size localization band

$$\sigma_{eq} = \sqrt{C+F}\,|\sigma_{22}|, \quad \dot{\varepsilon}^p_{22} = \dot{p}\,\sqrt{C+F}, \quad \dot{p} = \frac{2\mu\sqrt{C+F}\dot{\varepsilon}_{22}}{2\mu(C+F)+H}$$

$$\begin{cases} (\sigma_{22}+s_{22})_{,2} = 0, \quad S_{222,2}+s_{22} = 0 \\ \sigma_{22} = 2\mu(\varepsilon_{22}-\varepsilon^p_{22}) = \frac{2\mu}{2\mu(C+F)+H}(H\varepsilon_{22}+R_0\sqrt{C+F}) \\ s_{22} = 2\mu(\varepsilon_{22}-\chi_{22}), \quad S_{222} = A\chi_{22,2} \end{cases}$$

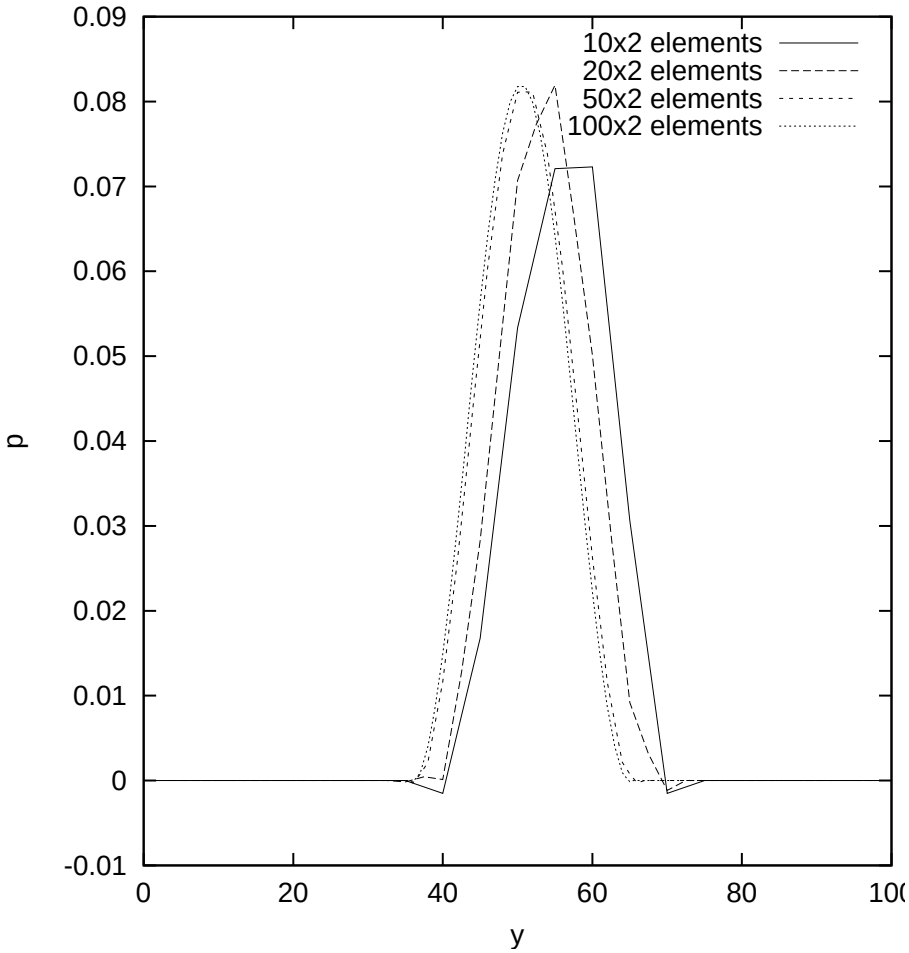
Finalement

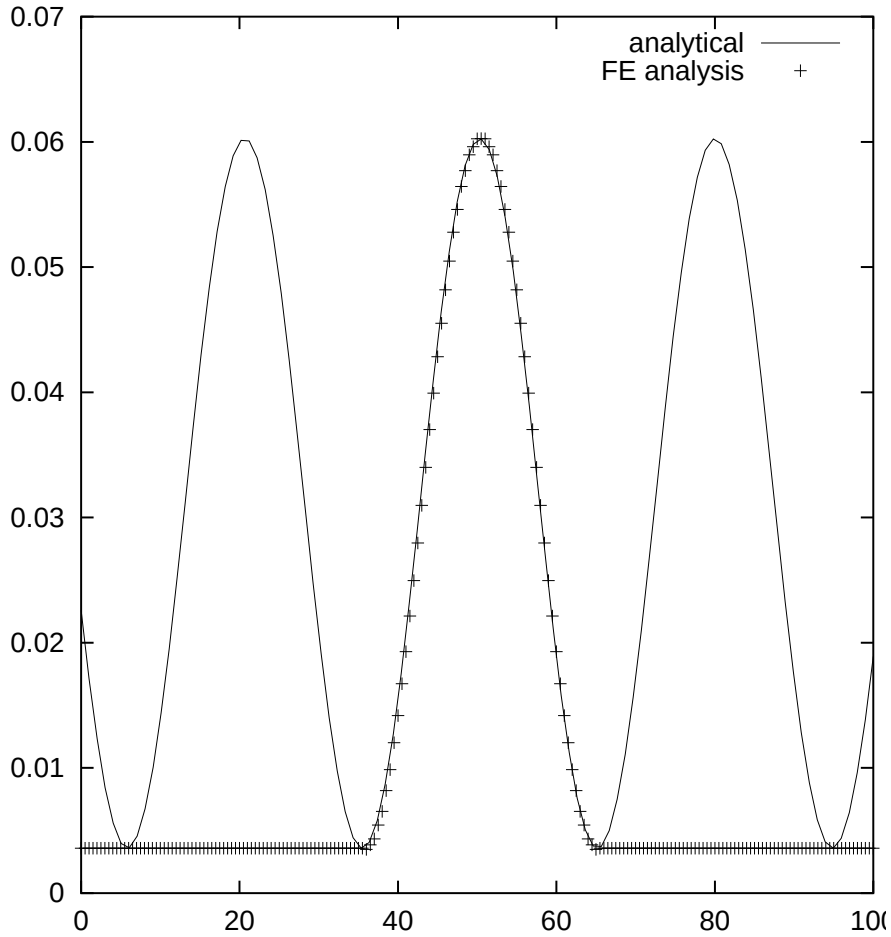
$$\chi_{22,222} - \frac{2\mu\bar{H}}{A(\bar{H}+2\mu)}\chi_{22,2} = 0, \quad \bar{H} = \frac{2\mu H}{2\mu(C+F)+H}$$

Longueur d'onde

$$\frac{1}{\omega} = \sqrt{\frac{A(\bar{H}+2\mu)}{2\mu|\bar{H}|}}$$

Finite size localization band

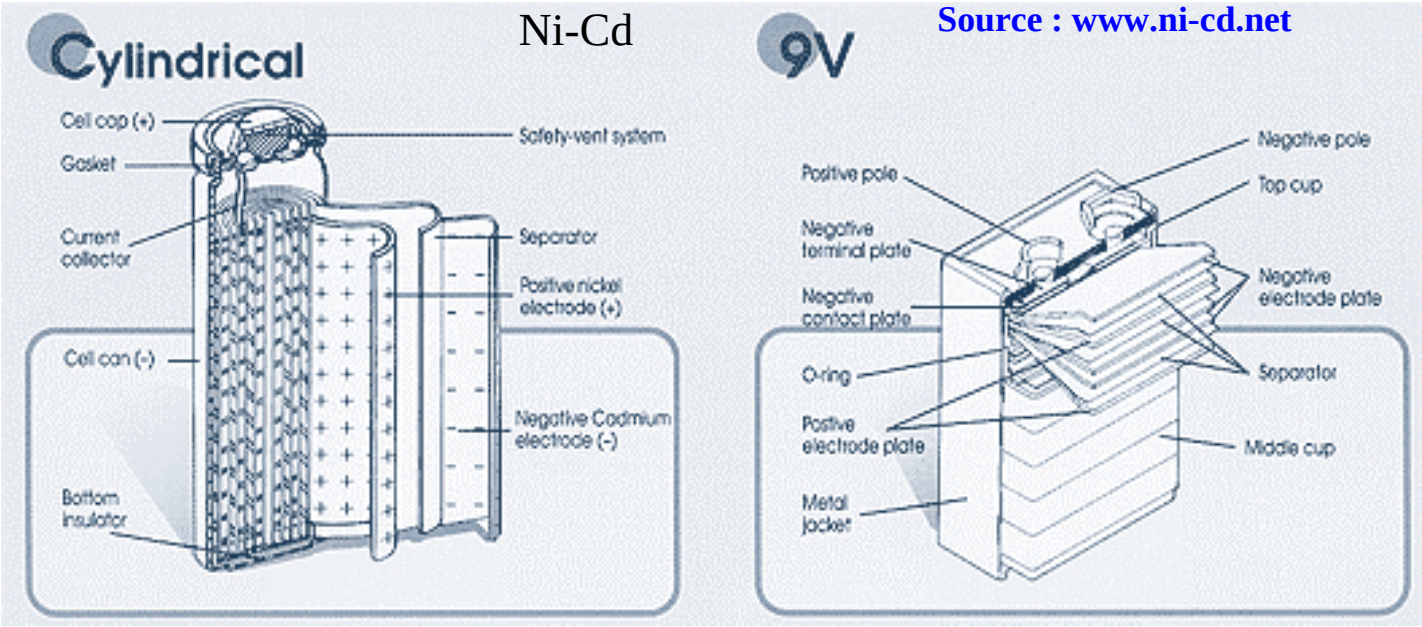




Industrial applications

battery applications : portable computers, mobile phones …

➡ positive electrode base (Ni-Cd, Ni-M-H batteries)



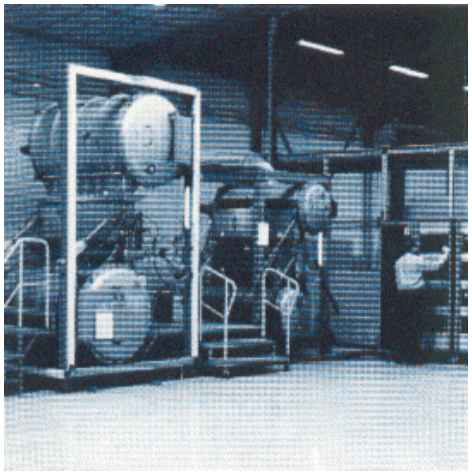
- good electrical conductivity

- high content of electrolyte (96% of voids)

Nickel foam process (NiTECH)

polyurethane foam

(coils)



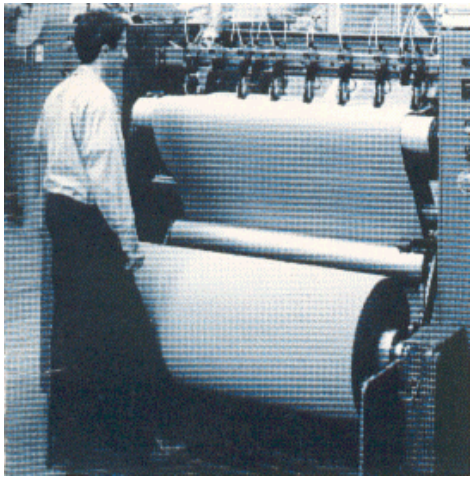
magnetron
nickel
sputtering
(P.V.D)

electrolysis

heat treatment

- pyrolysis

- annealing



RD : coiling direction

Microstructure of nickel foams

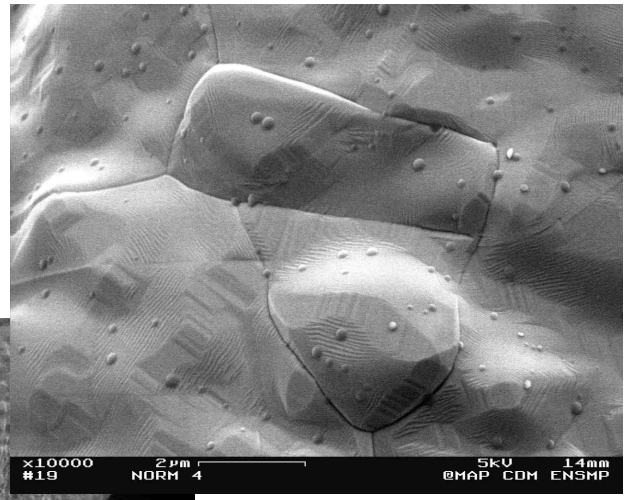
relative densities (ρ/ρ_{Ni}) : 0,024 to 0,035

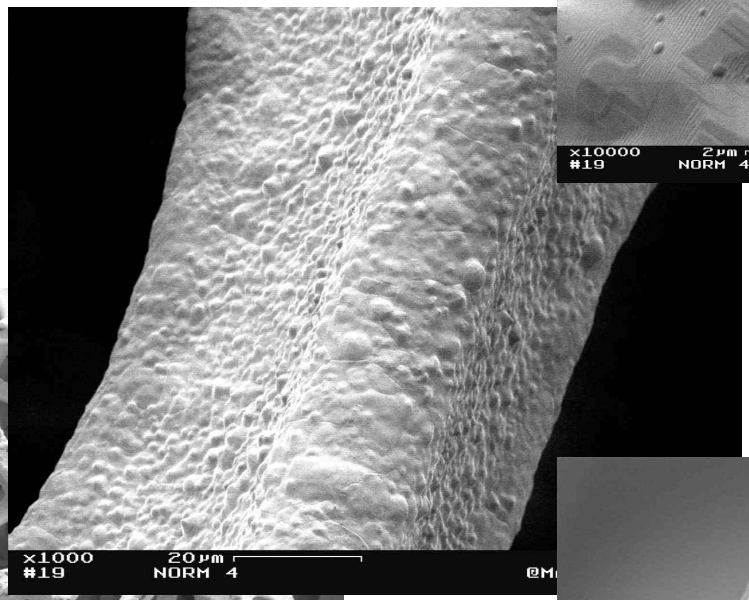
Cell size ~ 500 µm

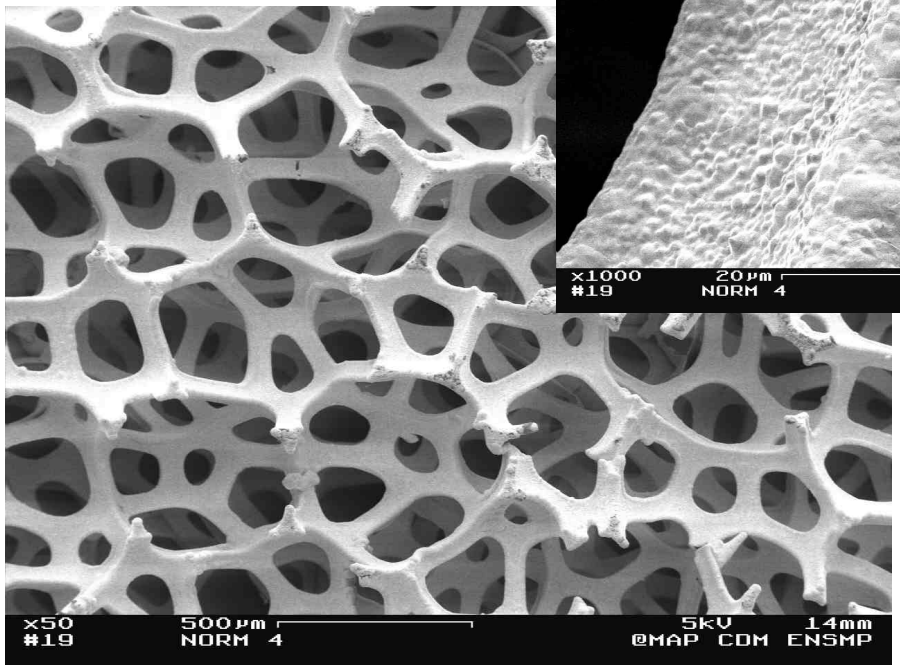
Strut length ~ 180 µm

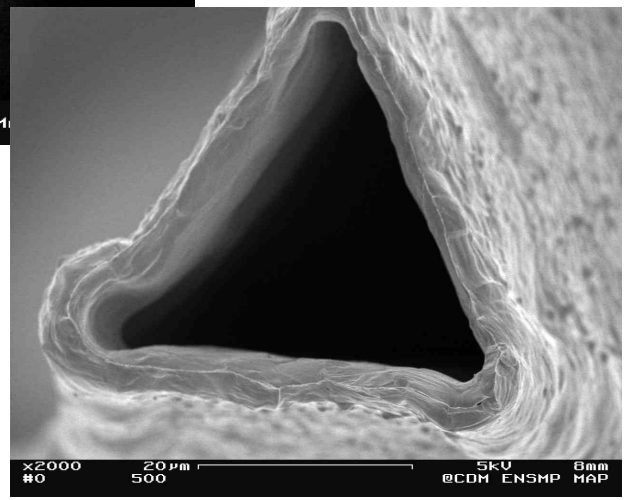
Strut thickness ~ 10 µm

Grain size ~ 8 µm



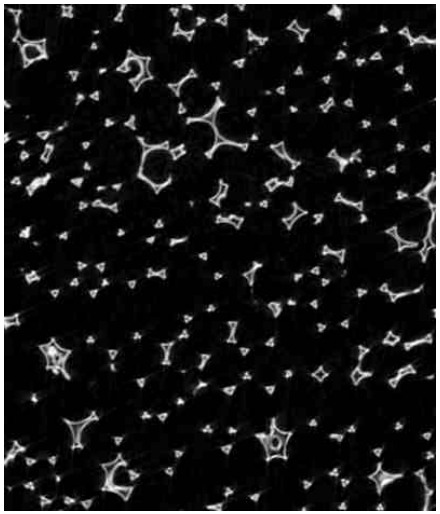




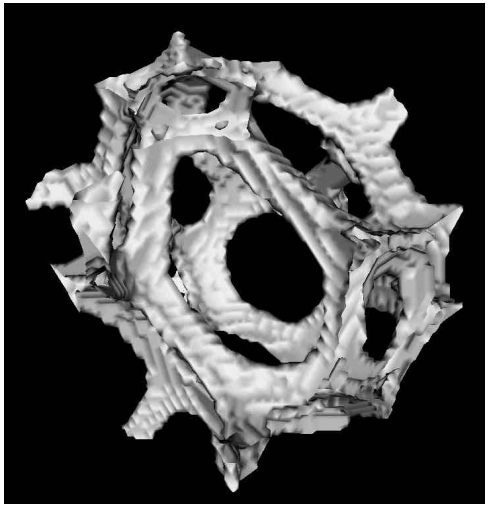


Morphology of the cells

Obtained by microtomography at E.S.R.F. (Grenoble)

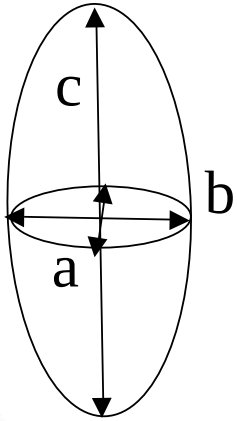


2D section



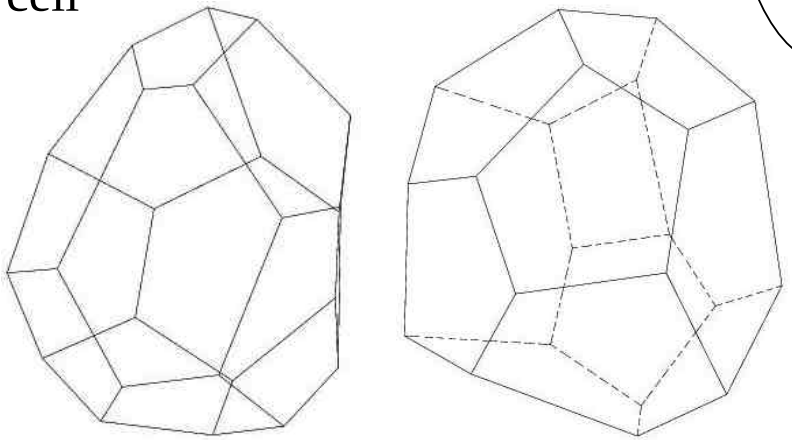
3D reconstruction of the cell

Geometry aspect ratio between RD and TD : R= a/b =1,3



Shape of the cell :

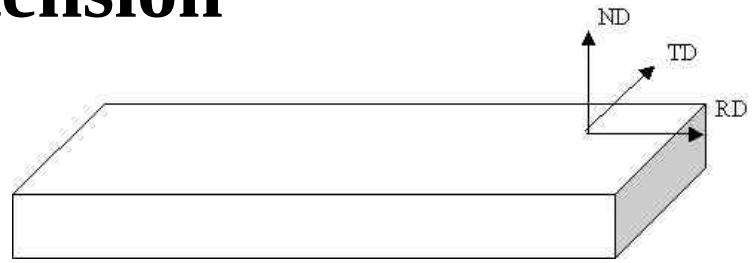
pentagonal, hexagonal and quadrilateral faces

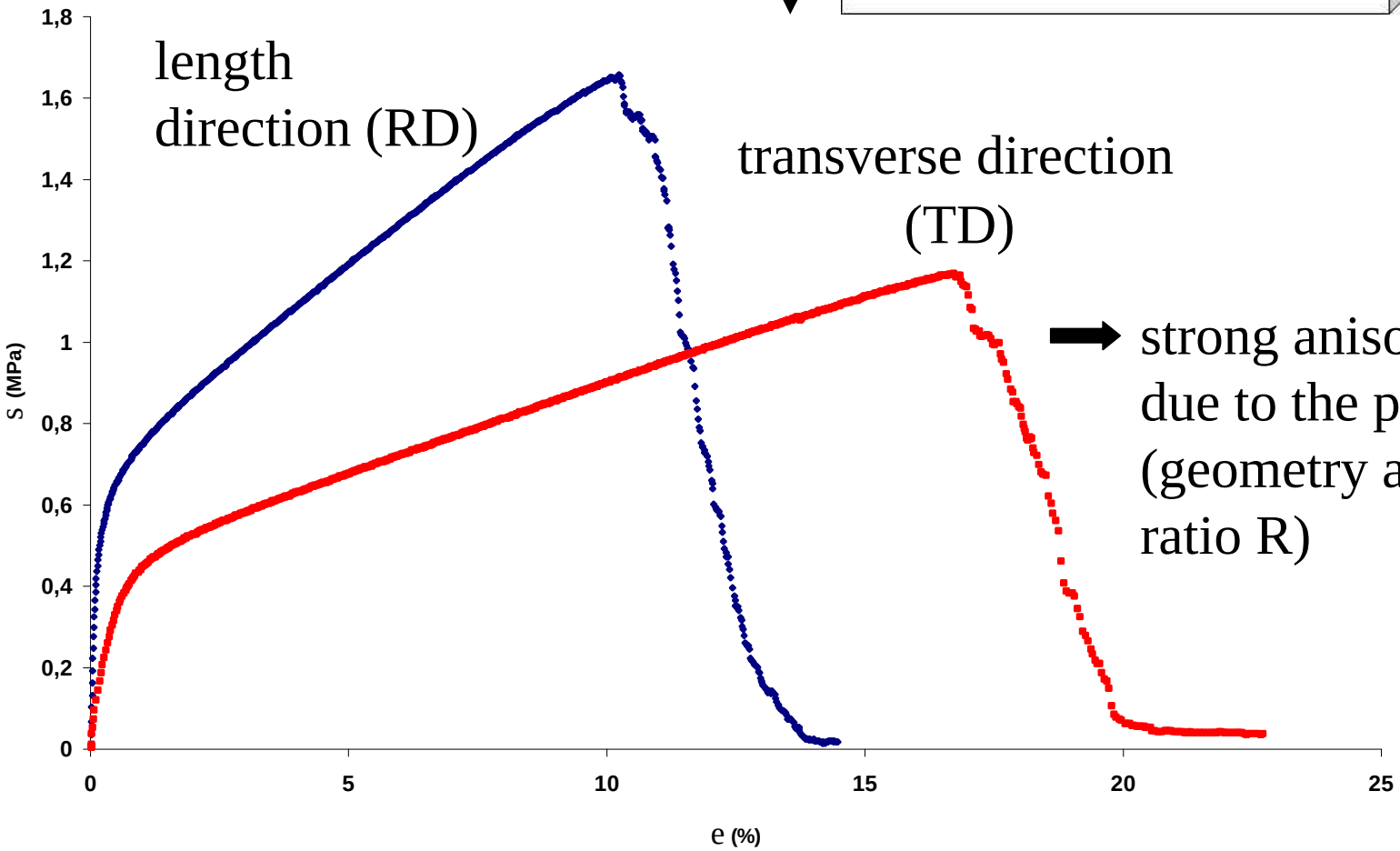


Mechanical behaviour in tension

500 g/m²

e = 1.7 mm

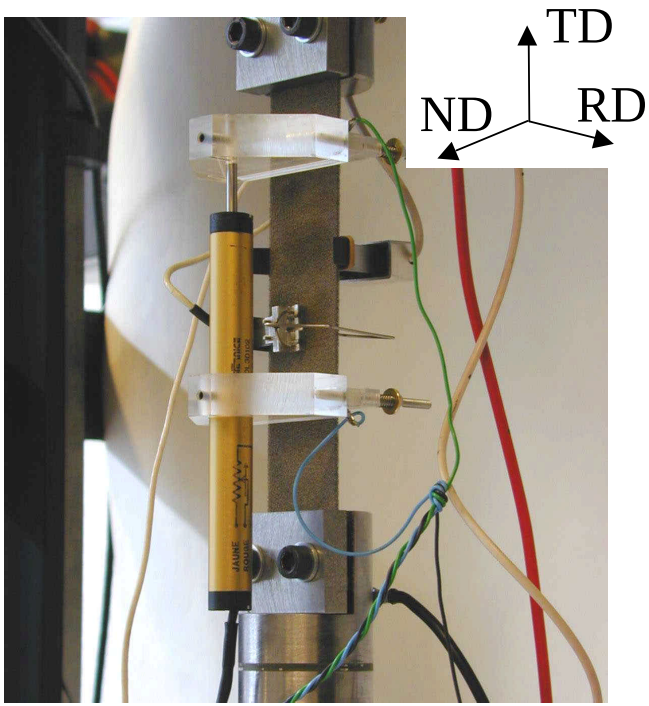


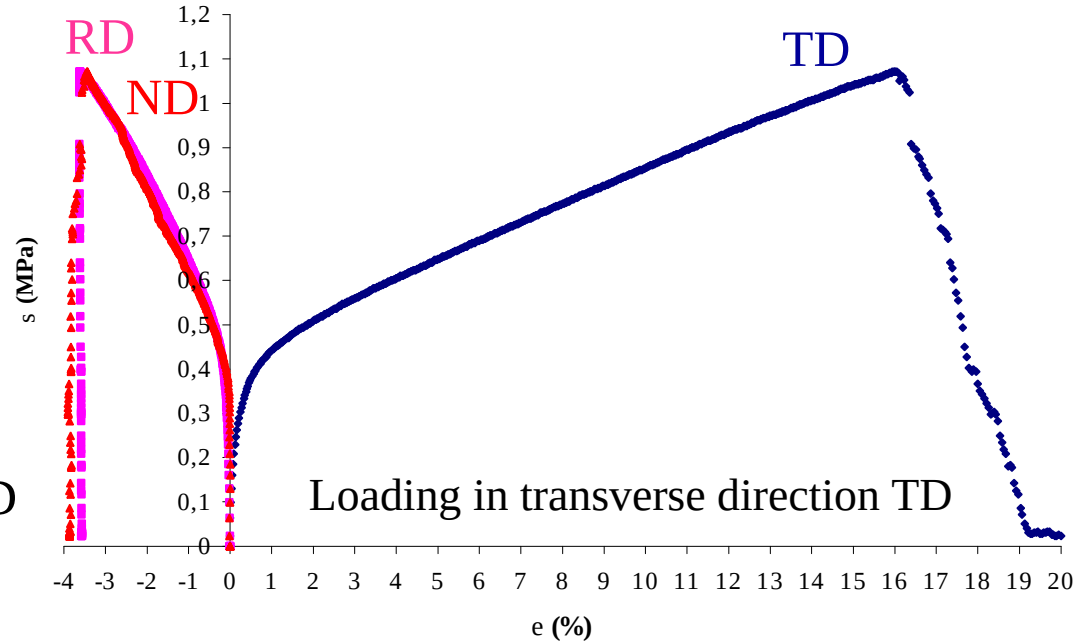


➡ strong anisotropy due to the process (geometry aspect ratio R)

Foam : a compressible material

Deformation measurements in the 3 directions at the same time





Poisson ratios :

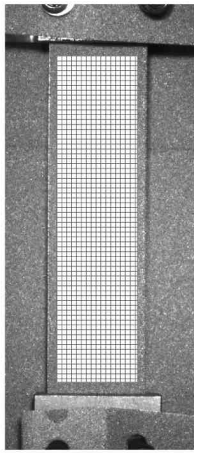
$$n_{RT} = -\frac{e_{RD}}{e_{TD}} = 0{,}22 \qquad n_{NT} = -\frac{e_{ND}}{e_{TD}} = 0{,}24$$

Photomechanical device

Rectangular grid :

77 lines x 19 rows

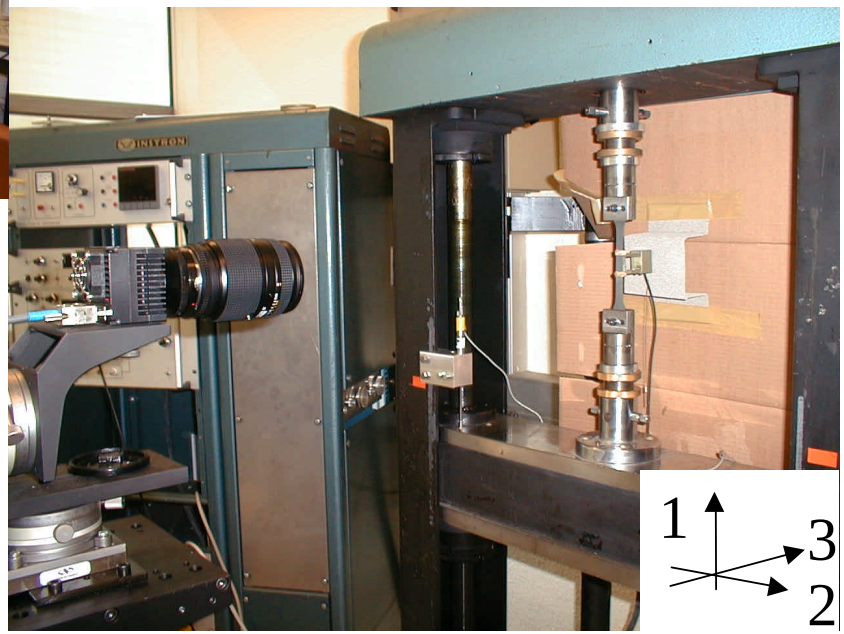
→ 1463 points



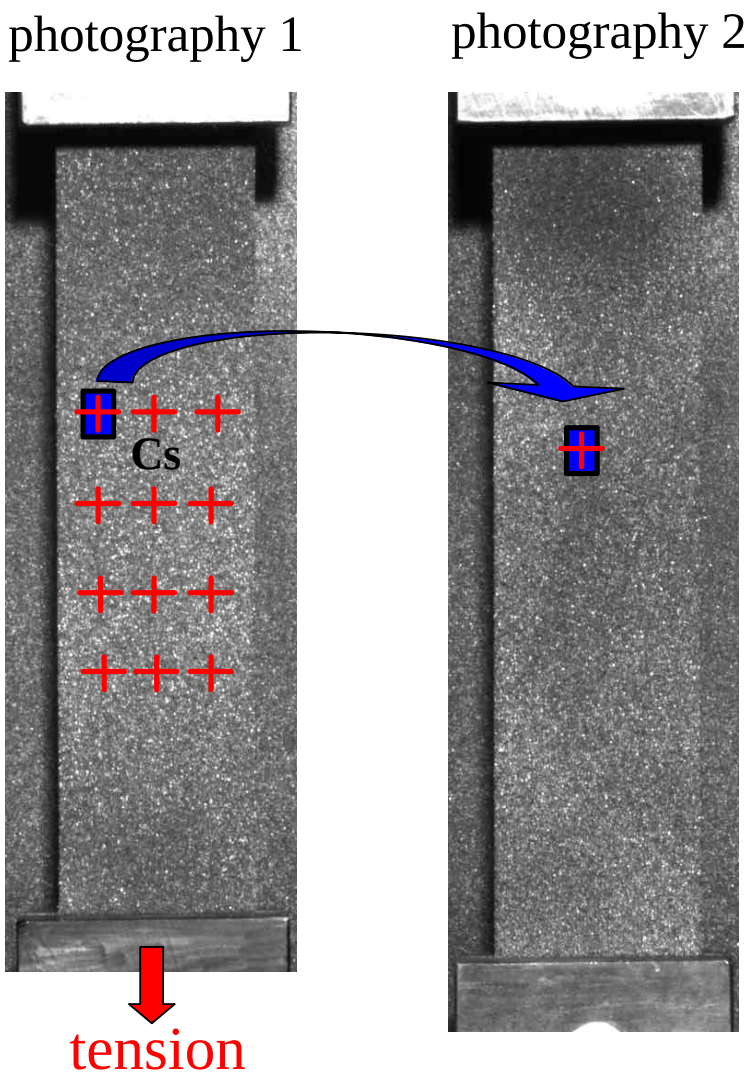
High resolution C.C.D. camera (1300x1030)

Standard lens 35-70 mm

Non coherent light (spot 30 W)



Digital correlation method



Principle :

search the grey level distribution of the neighbourhood of each point of the grid in photography 2

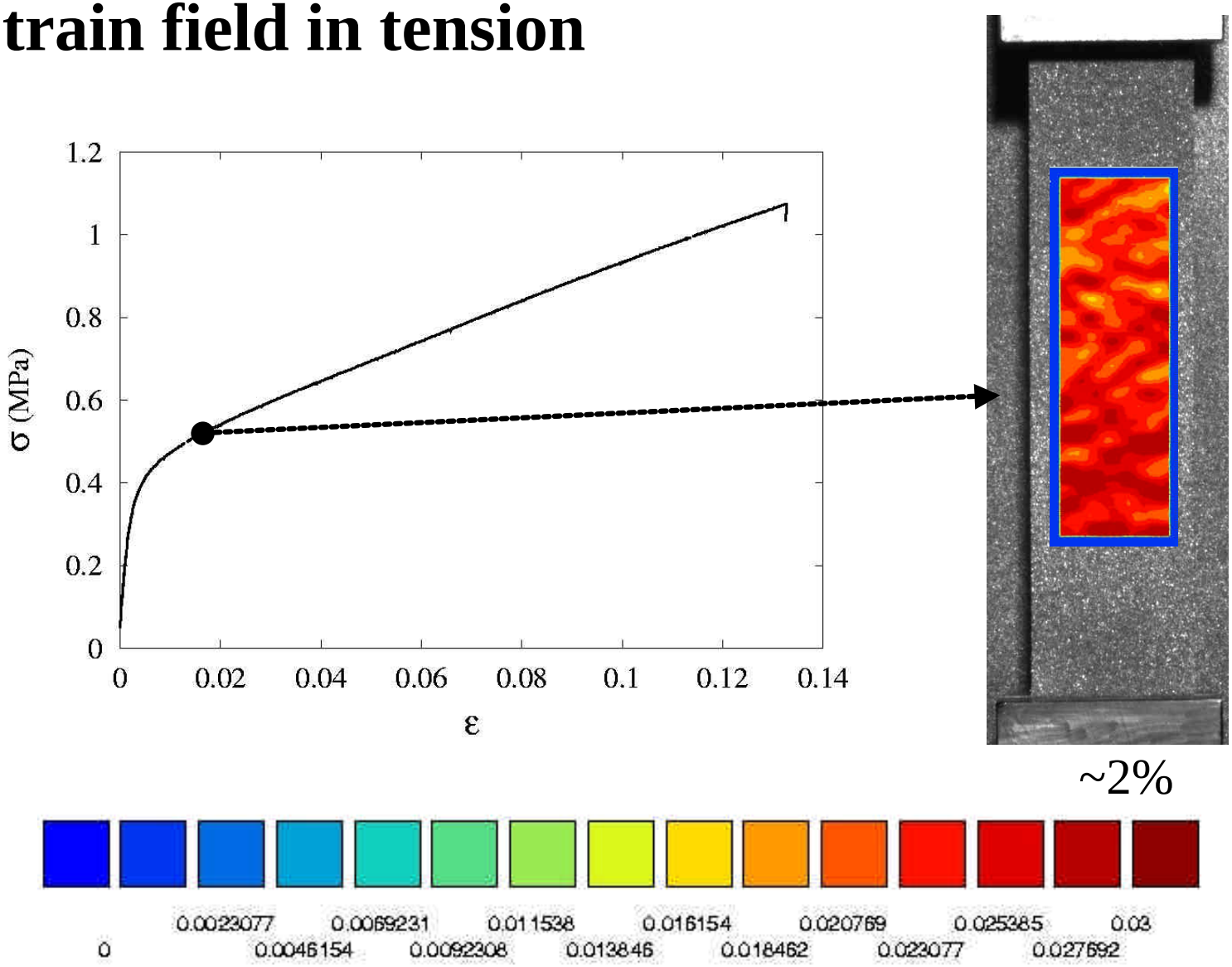
Inter-correlation function :

$$j_{\mathrm{Im1,Im2}}(u,v)=\sum_{u=-\infty}^{+\infty}\sum_{v=-\infty}^{+\infty}\mathrm{Im1}(x,y)\,\mathrm{Im2}(x+u,y+v)$$

C_s : correlation size

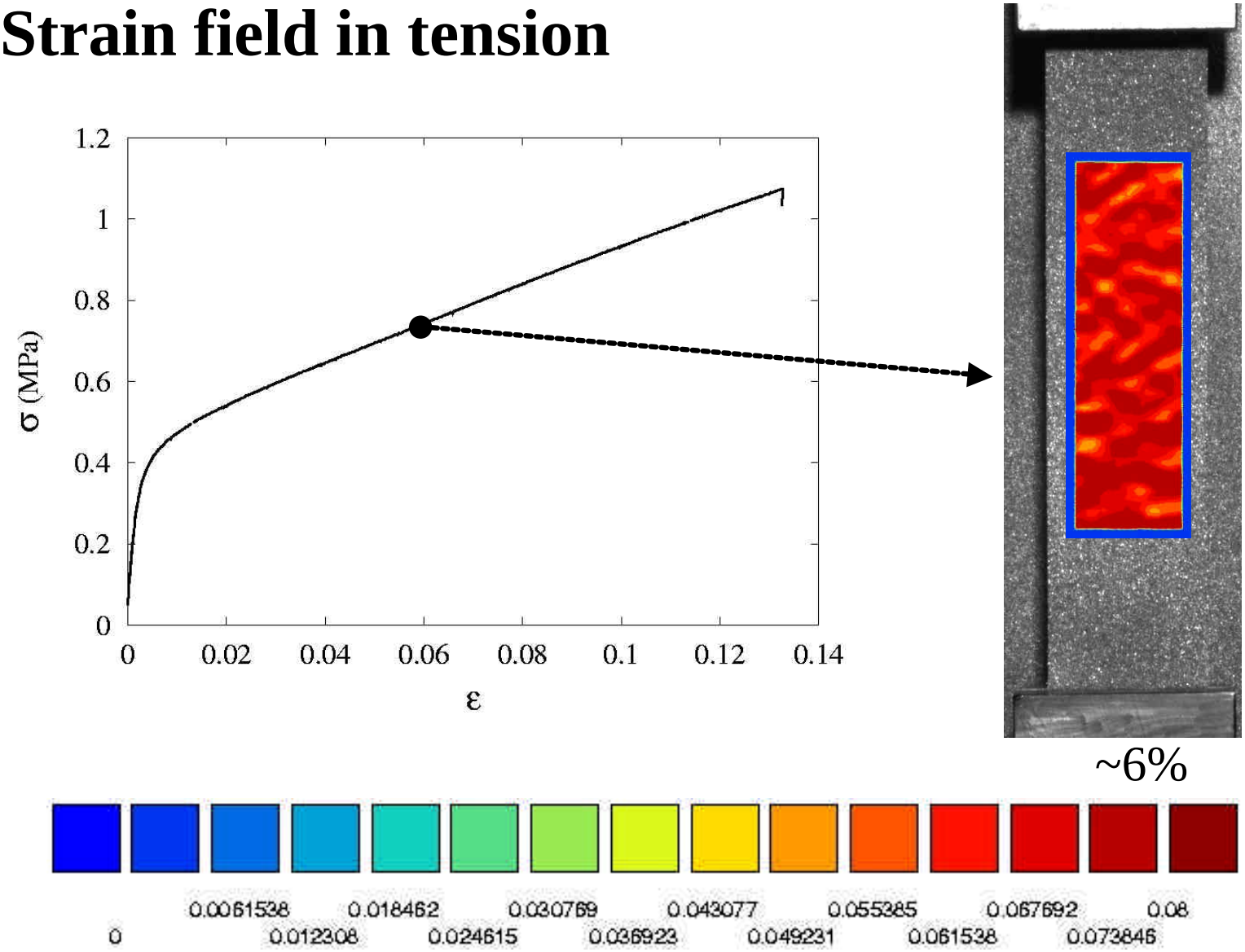
Chosen resolution : 136 µm/pix

Strain field in tension



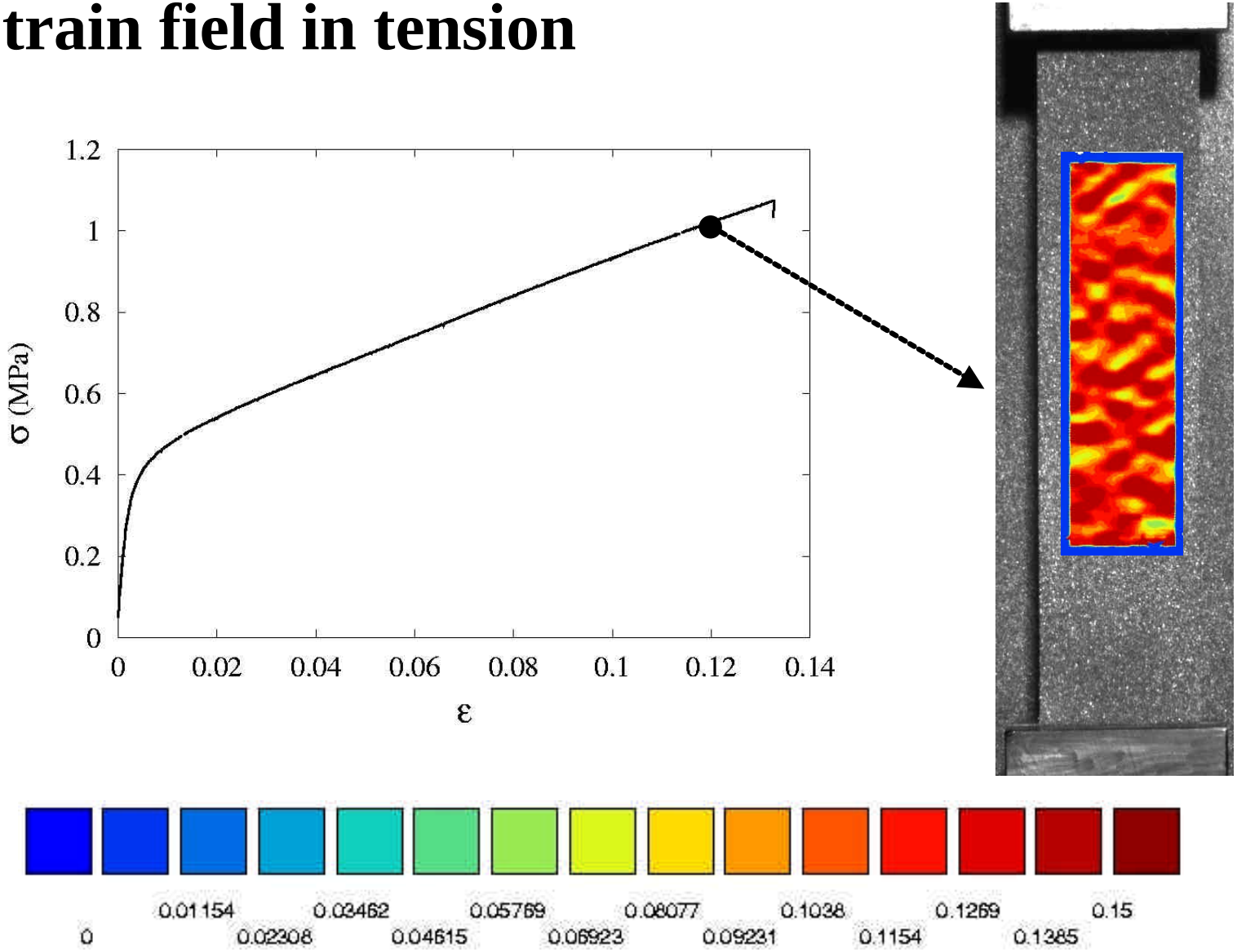
collaboration Ecole des Mines d'Alès (P. Ienny)

Strain field in tension



collaboration Ecole des Mines d'Alès (P. Ienny)

Strain field in tension



~12%

collaboration Ecole des Mines d'Alès (P. Ienny)

Anisotropic Compressible Continuum Plasticity Model

Yield criterion

$$f(\underset{\sim}{\boldsymbol{\sigma}}) = \sigma_{eq} - R, \quad \sigma_{eq} = \left(\frac{3}{2} C \underset{\sim}{\boldsymbol{\sigma}}^{\mathrm{dev}} : \underset{\sim}{\boldsymbol{H}} : \underset{\sim}{\boldsymbol{\sigma}}^{\mathrm{dev}} + F(\underset{\sim}{\boldsymbol{P}} : \underset{\sim}{\boldsymbol{\sigma}})^2 \right)^{\frac{1}{2}}$$

$$[H] = \begin{bmatrix} h_a & 0 & 0 & 0 & 0 & 0 \\ 0 & h_b & 0 & 0 & 0 & 0 \\ 0 & 0 & h_c & 0 & 0 & 0 \\ 0 & 0 & 0 & h_d & 0 & 0 \\ 0 & 0 & 0 & 0 & h_e & 0 \\ 0 & 0 & 0 & 0 & 0 & h_f \end{bmatrix}, \quad [P] = \begin{bmatrix} p & 0 & 0 \\ 0 & q & 0 \\ 0 & 0 & r \end{bmatrix}$$

Normality rule

$$\dot{\underset{\sim}{\boldsymbol{\varepsilon}}}^p = \dot{p} \frac{\partial f}{\partial \underset{\sim}{\boldsymbol{\sigma}}} = \dot{p} \left(\frac{3}{2} C \underset{\sim}{\boldsymbol{H}} : \underset{\sim}{\boldsymbol{\sigma}}^{\mathrm{dev}} + F(\underset{\sim}{\boldsymbol{P}} : \underset{\sim}{\boldsymbol{\sigma}}) \underset{\sim}{\boldsymbol{P}} \right)$$

Consistency condition (cumulative plastic strain p)

$$\dot{p} = \frac{\dfrac{\partial f}{\partial \underset{\sim}{\boldsymbol{\sigma}}} : \underset{\approx}{\boldsymbol{E}} : \underset{\sim}{\dot{\boldsymbol{\varepsilon}}}}{\dfrac{\partial f}{\partial \underset{\sim}{\boldsymbol{\sigma}}} : \underset{\approx}{\boldsymbol{E}} : \dfrac{\partial f}{\partial \underset{\sim}{\boldsymbol{\sigma}}} + \dfrac{\partial R}{\partial p}}$$

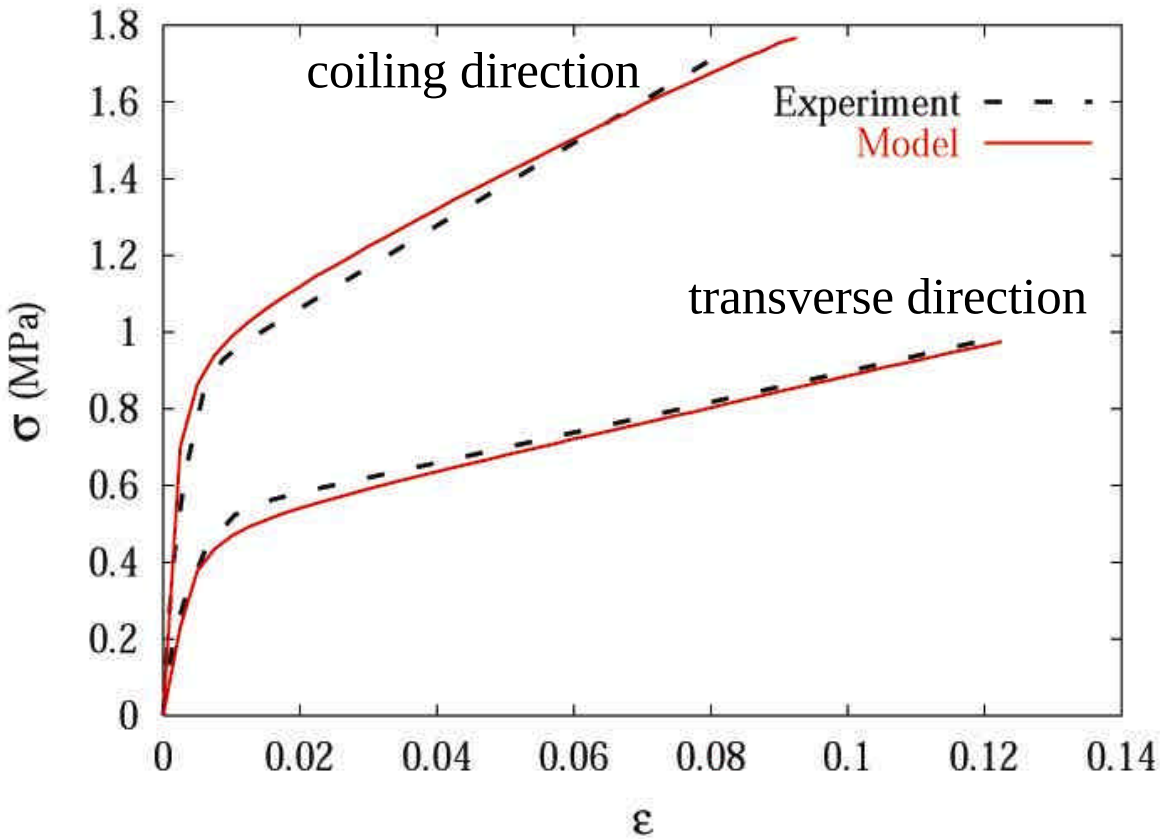
Nonlinear isotropic hardening

$$R = R_0 + Hp + Q(1 - \exp(-bp))$$

$\Longrightarrow$ parameters to identify : $C, F, \underset{\approx}{\boldsymbol{H}}, \underset{\sim}{\boldsymbol{P}}, R_0, H, Q, b$

Parameter identification

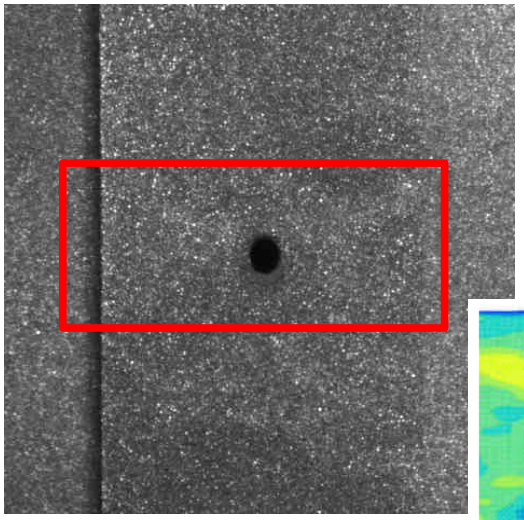
C	F	R_0 (MPa)	Q (MPa)	b	H (MPa)	h_a	h_b	h_c	h_d	h_e	h_f
1	$6{,}8.10^{-4}$	0,30	0,37	3,3	8,17	0,41	1,8	1,75	1,45	1	1

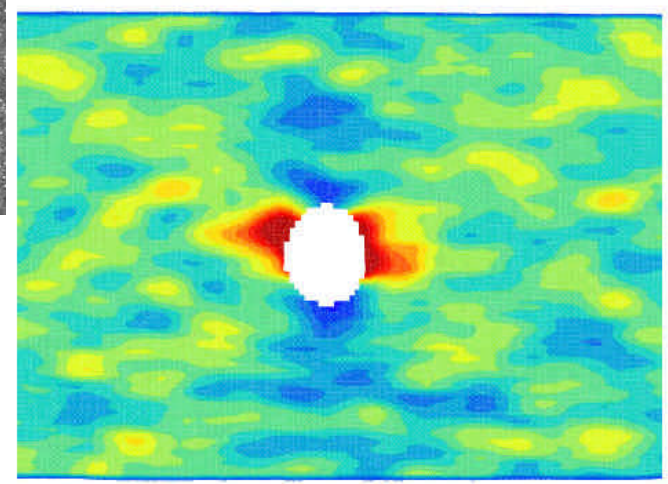


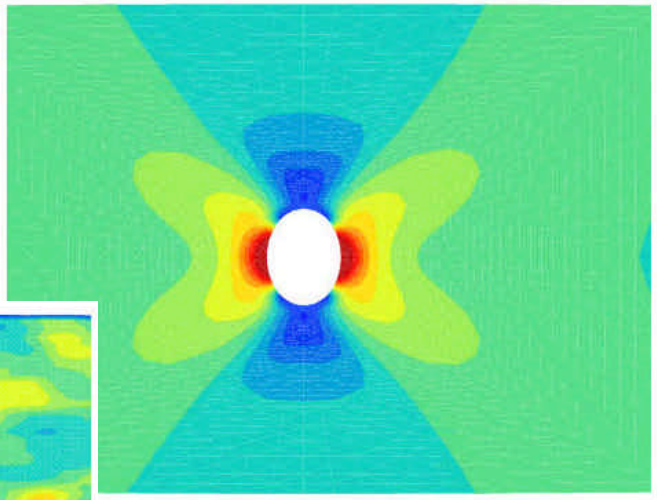
p	q	r
1	37	23

Strain field around a hole

Comparison between F.E. method and digital image correlation





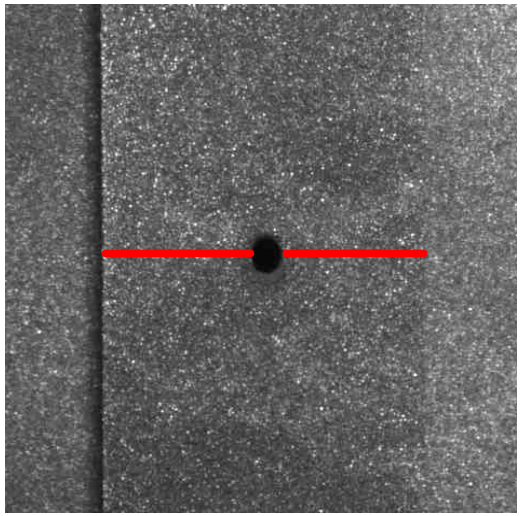


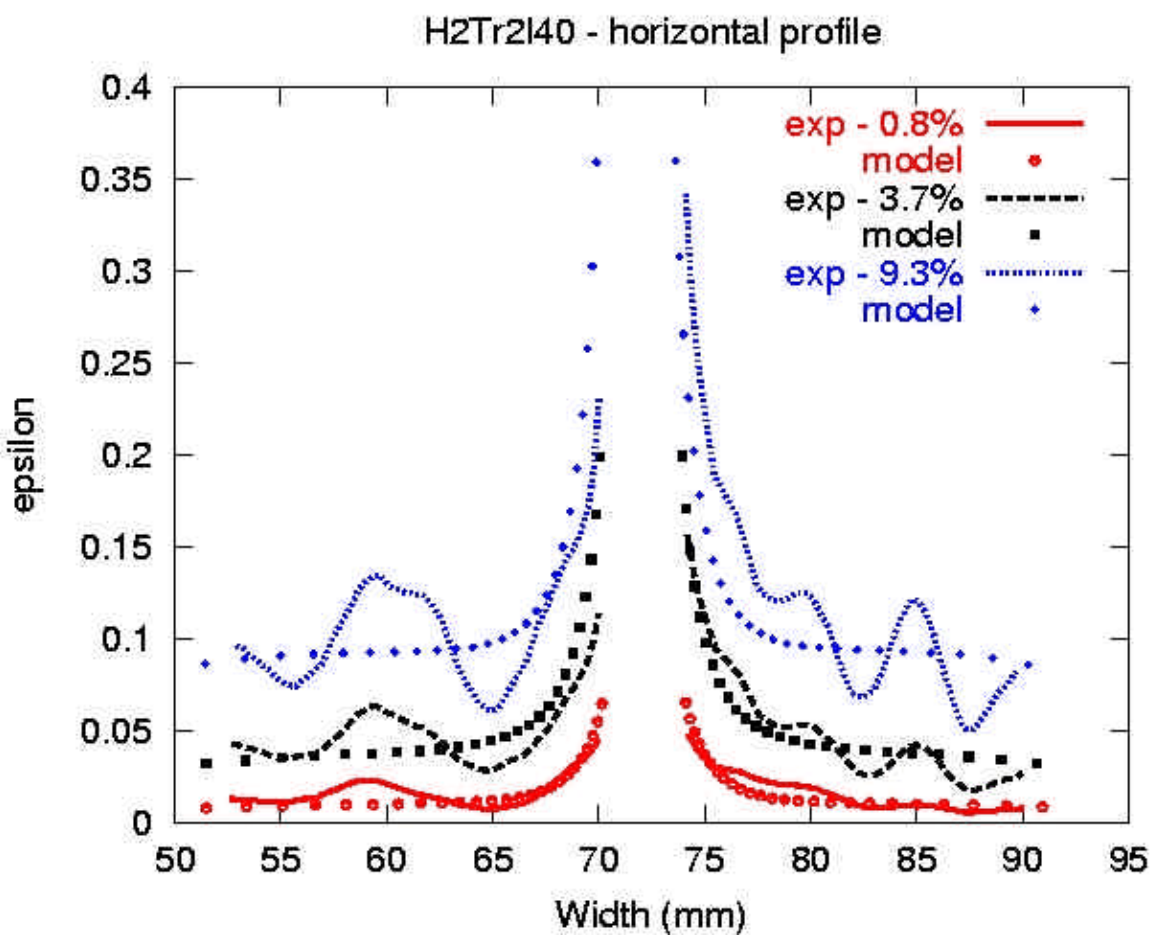
Fluctuations not depicted by the continuum model

Validity of the continuum model

Quantitative result along a horizontal line during deformation

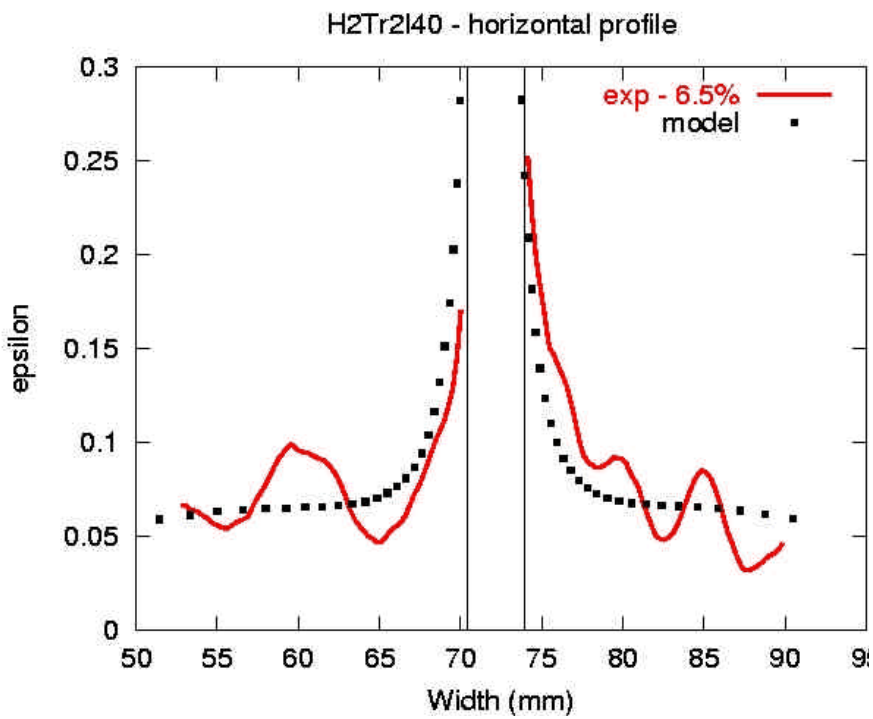
Hole radius = 2 mm



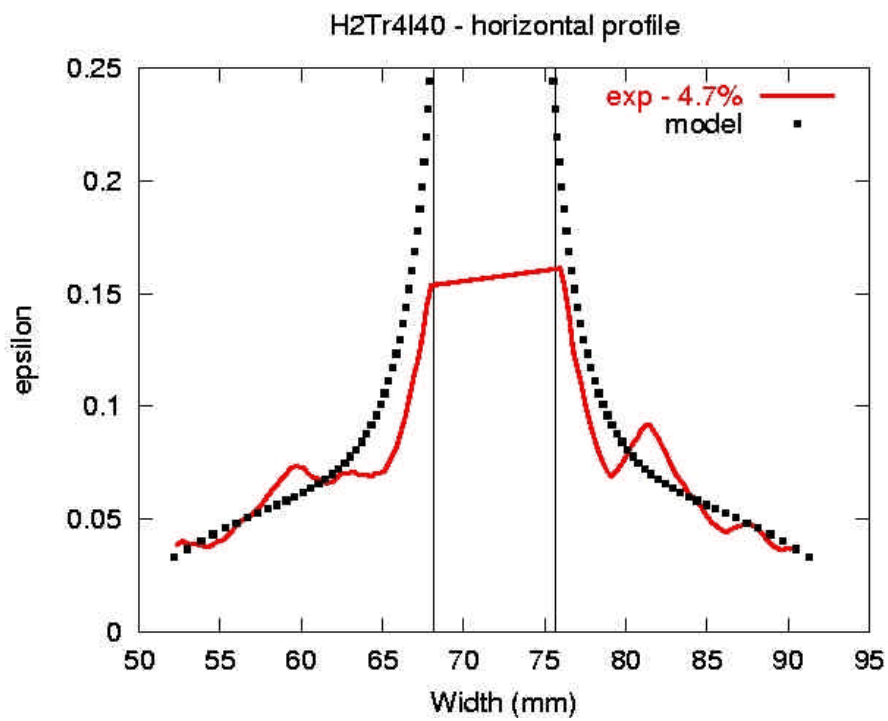


Hole size effect

Hole radius = 2 mm

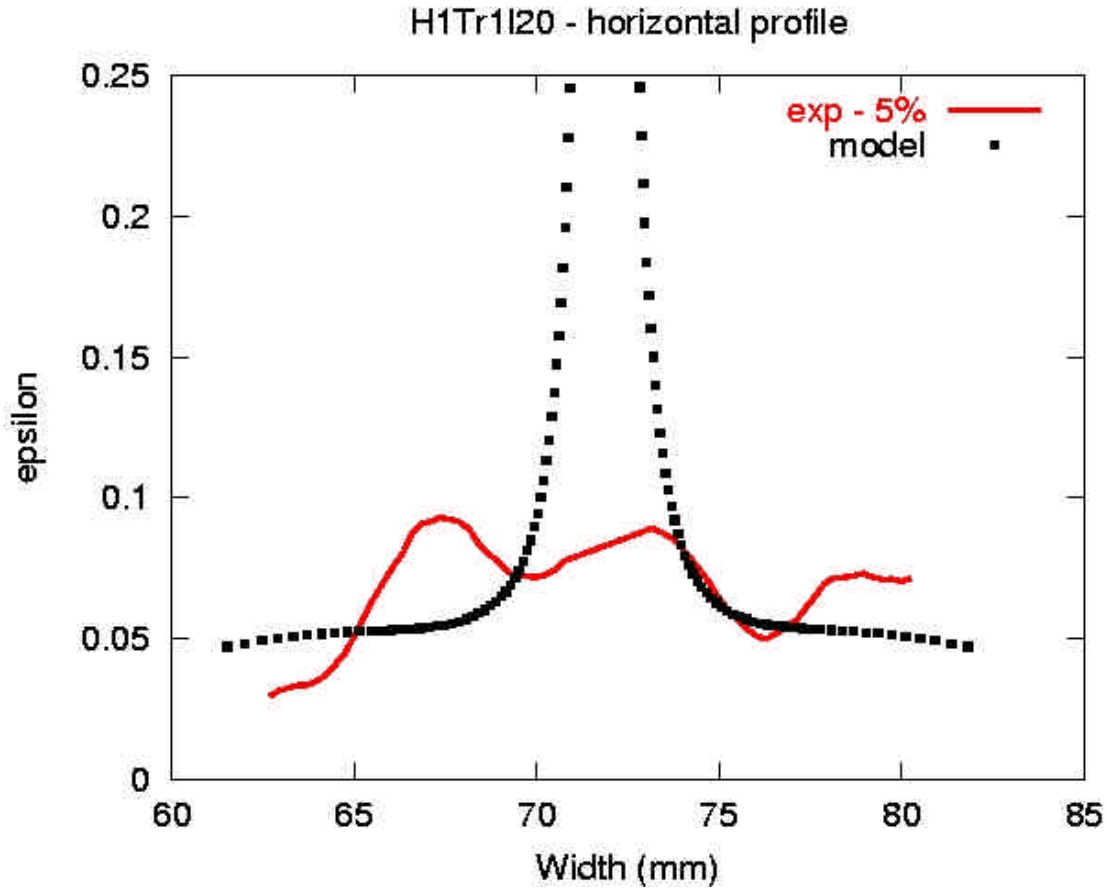


Hole radius = 4 mm



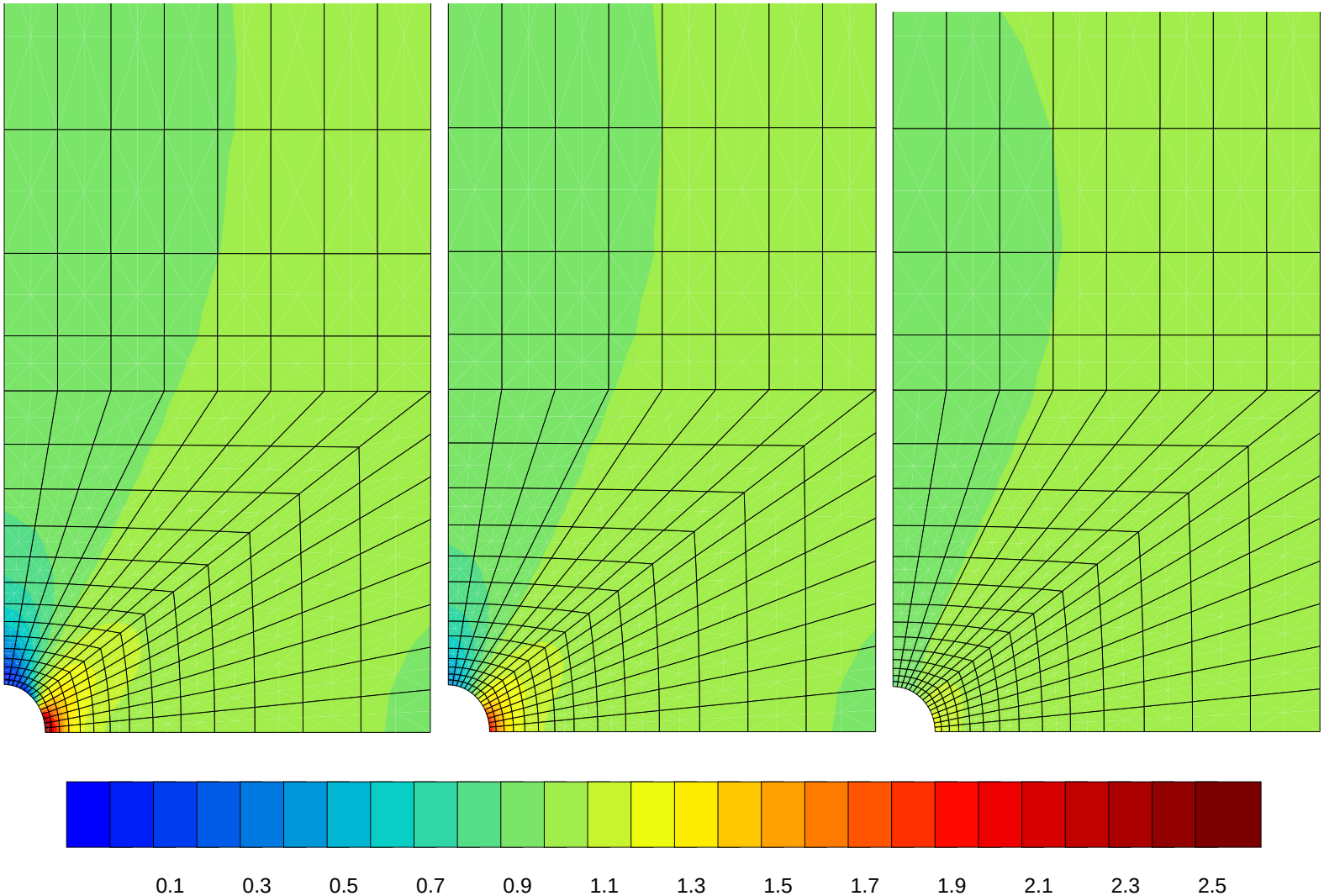
Hole size effect

Hole radius = 1 mm



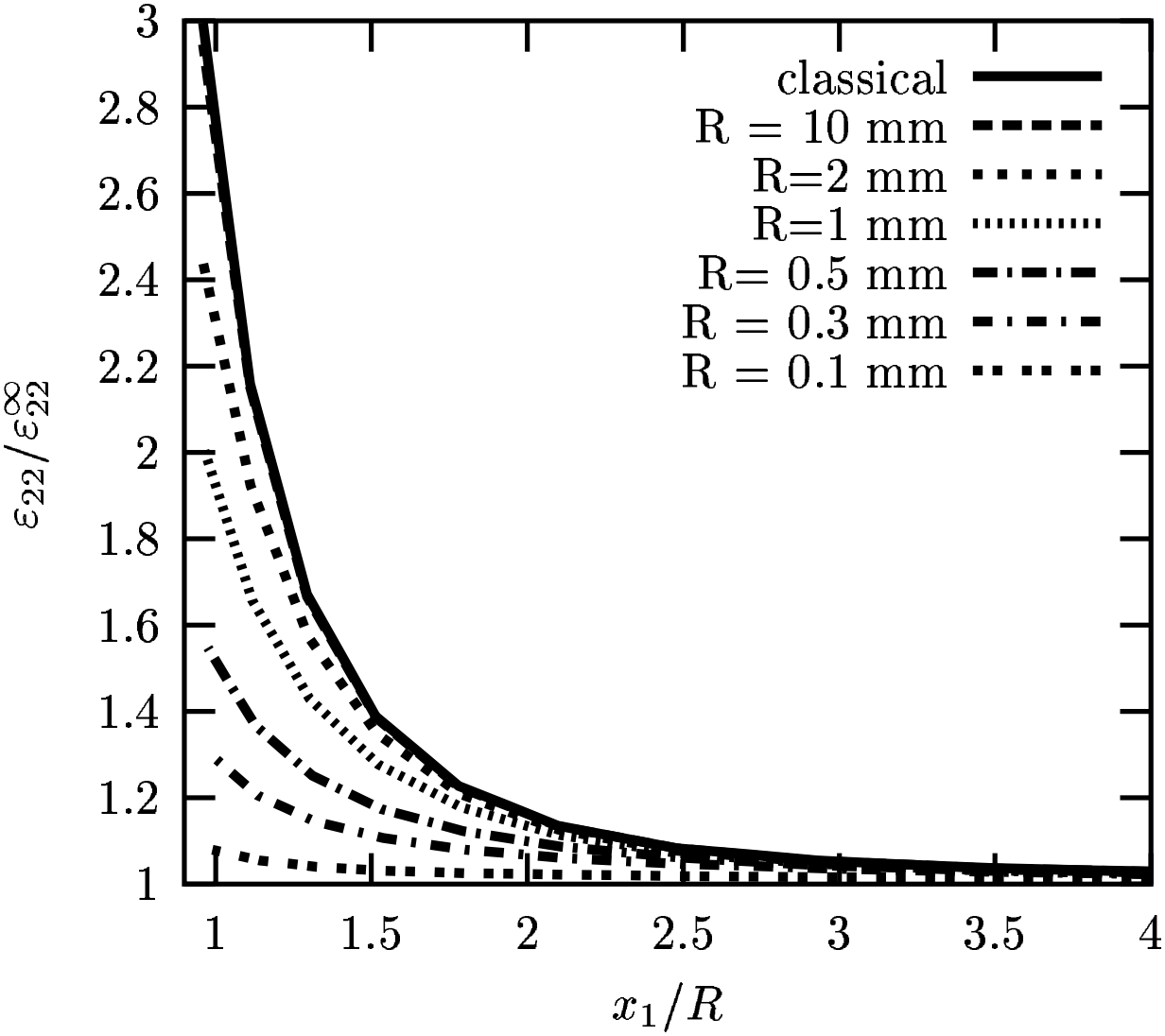
FE simulation of hole size effect in micromorphic elasticity

tension of a foam plate with a hole (axial strain component $\varepsilon_{22}/\varepsilon_{22}^{\infty}$) with $l_c = 0.31$ mm



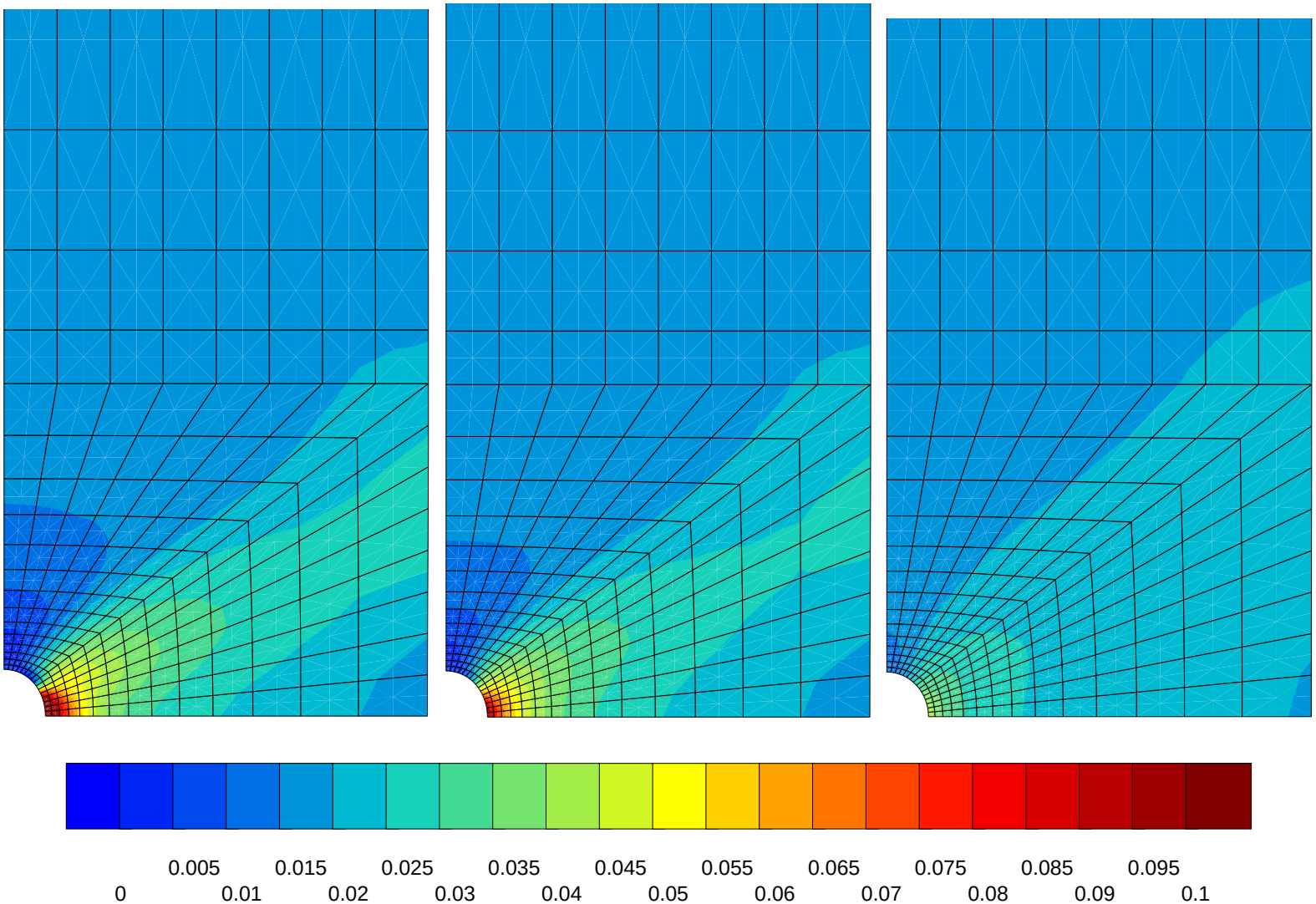
classical elasticity *microelasticity* $R = 1$ mm *microelasticity* $R = 0.3$ mm

FE simulation of hole size effect in micromorphic elasticity



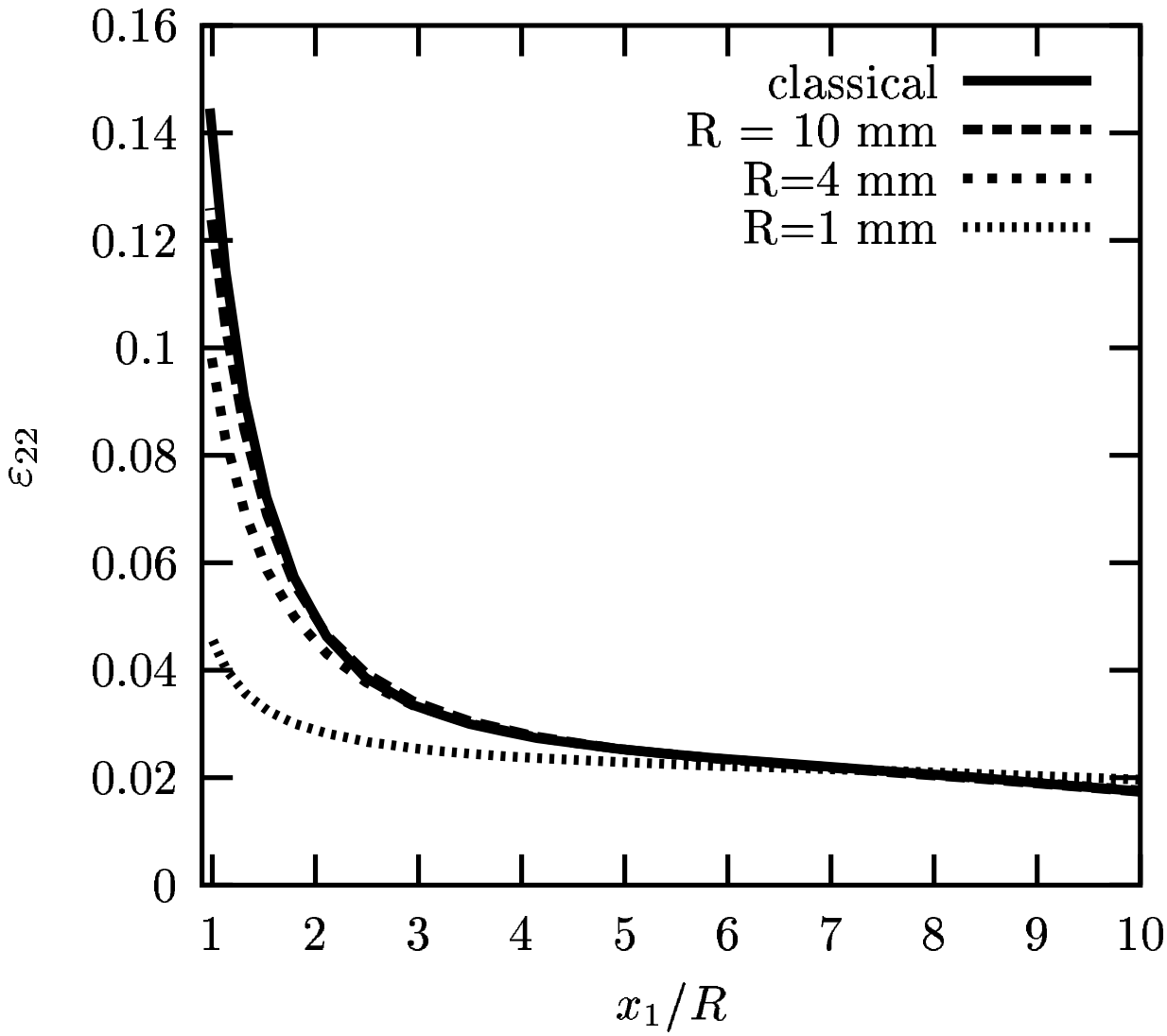
FE simulation of hole size effect in nickel foams

tension of a foam plate with a hole (axial strain component ε_{22}) with $l_c = 0.1$ mm

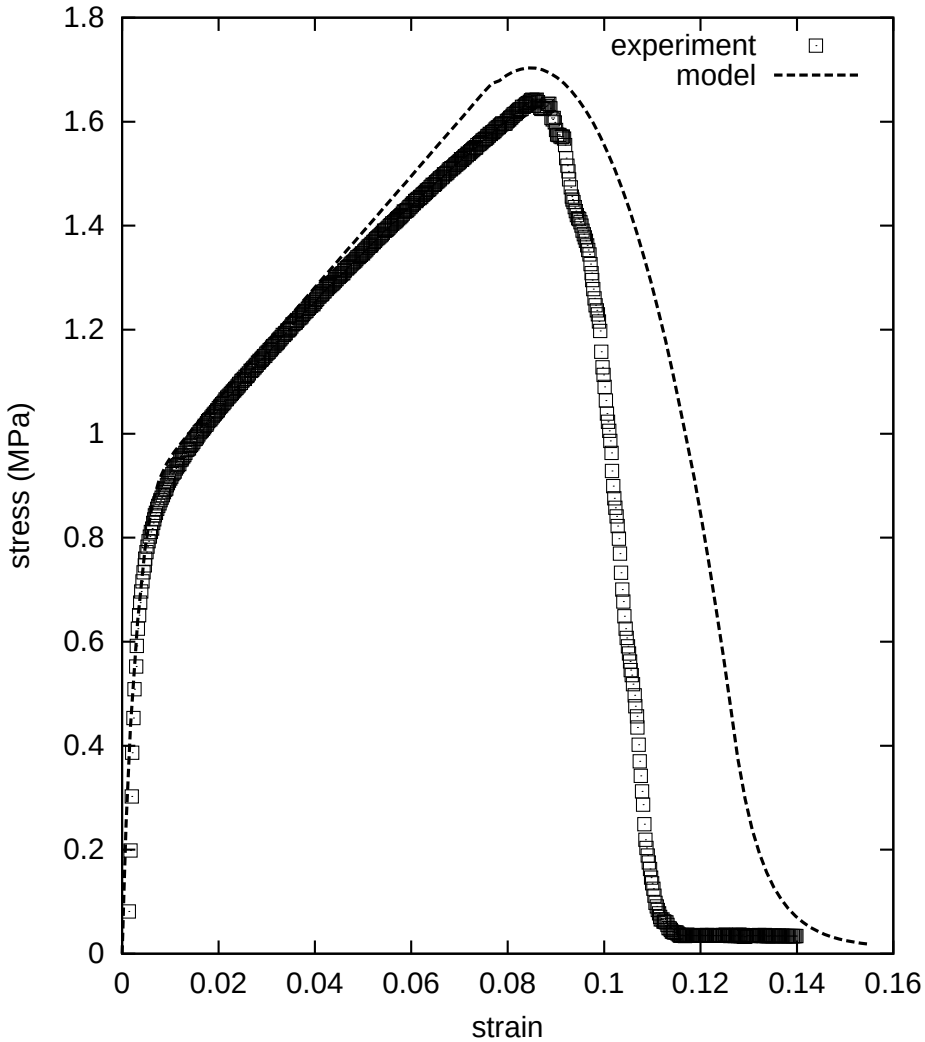


classical plasticity *microfoam* $R = 4$ mm *microfoam* $R = 1$ mm

FE simulation of hole size effect in nickel foams



Fracture of nickel foams



tensile test in direcion RD

simple fracture criterion

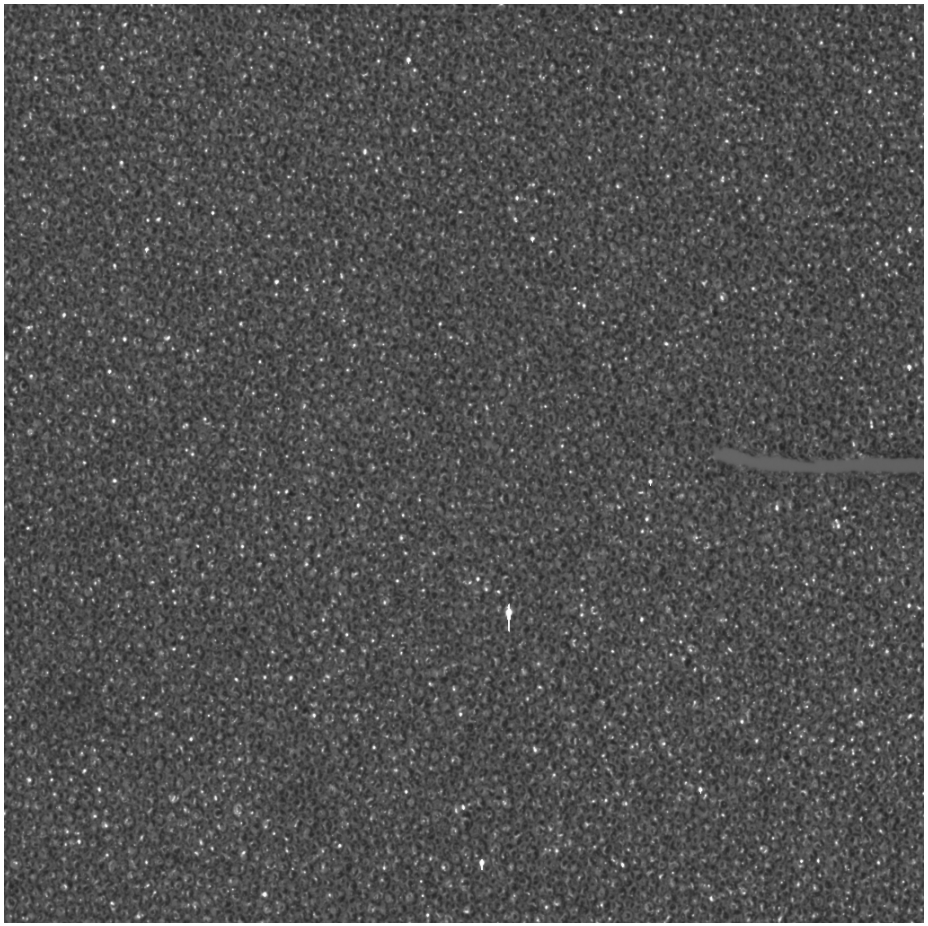
$$p = p_{crit} = 0.08$$

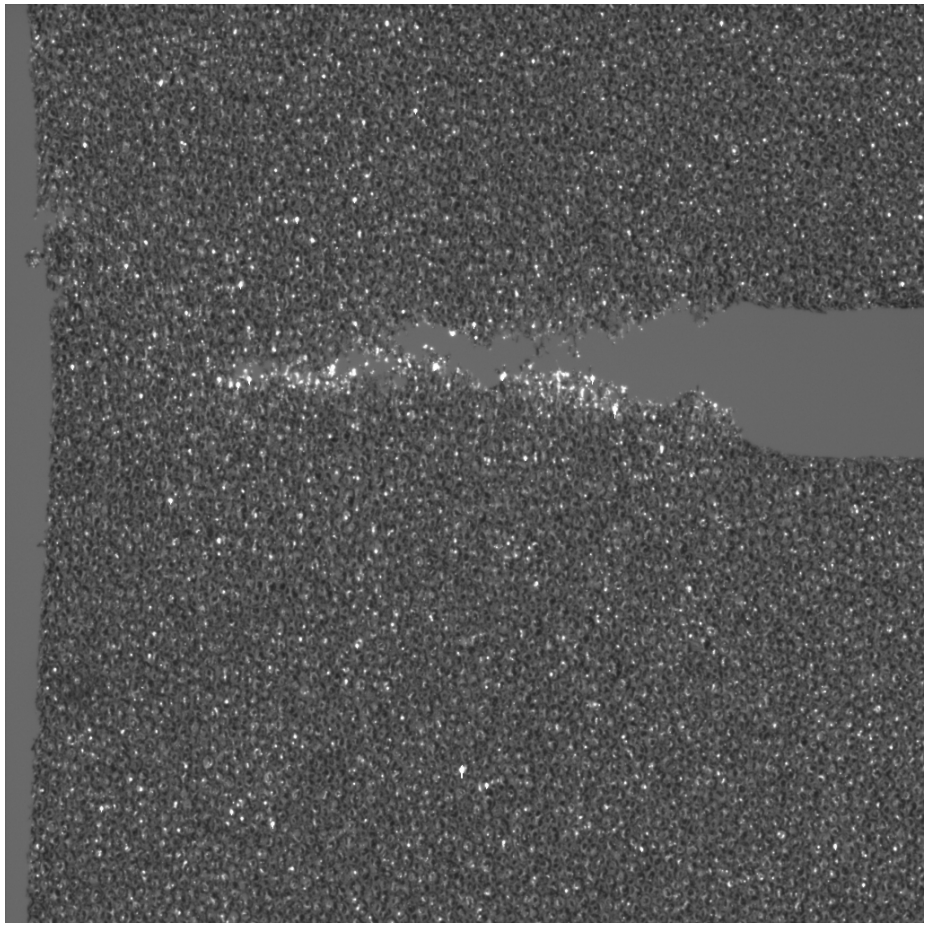
limited scatter in p_{crit}

softening law for $p > p_{crit}$

$$R = R(p > p_{crit})$$

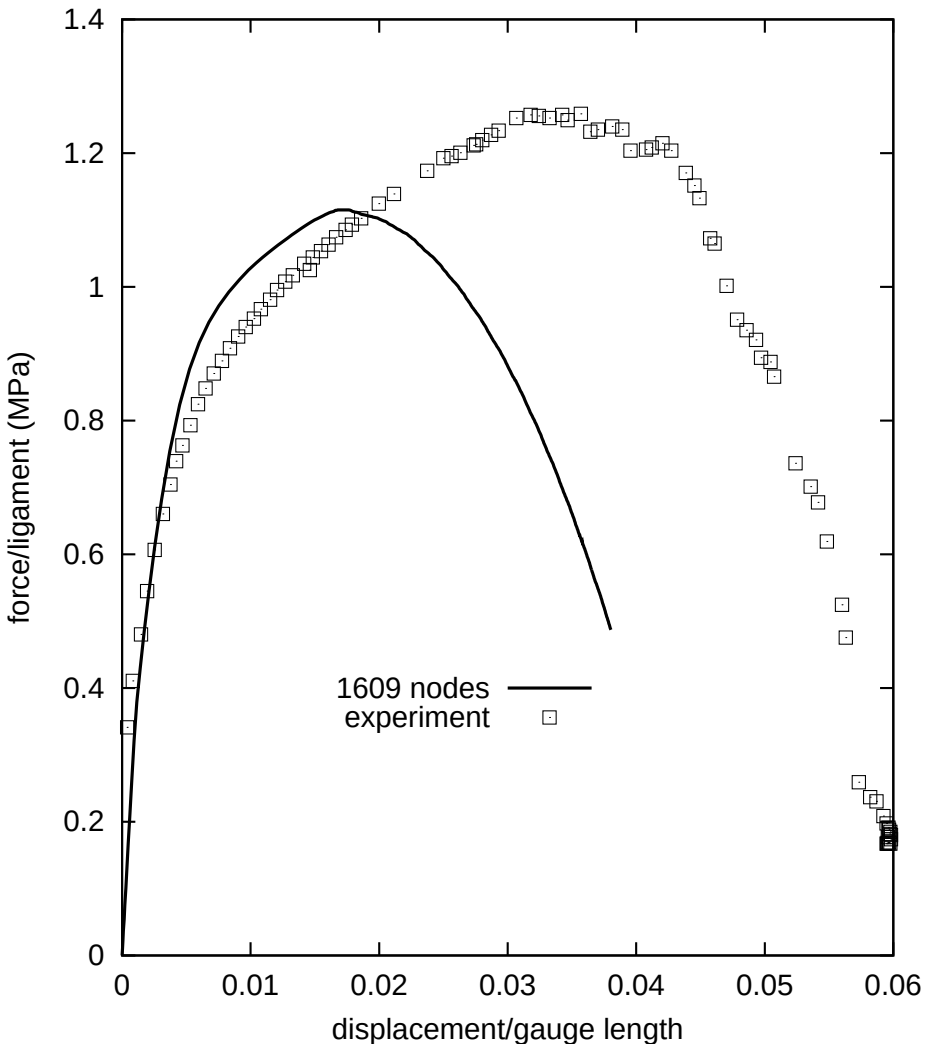
Tension of a cracked plate

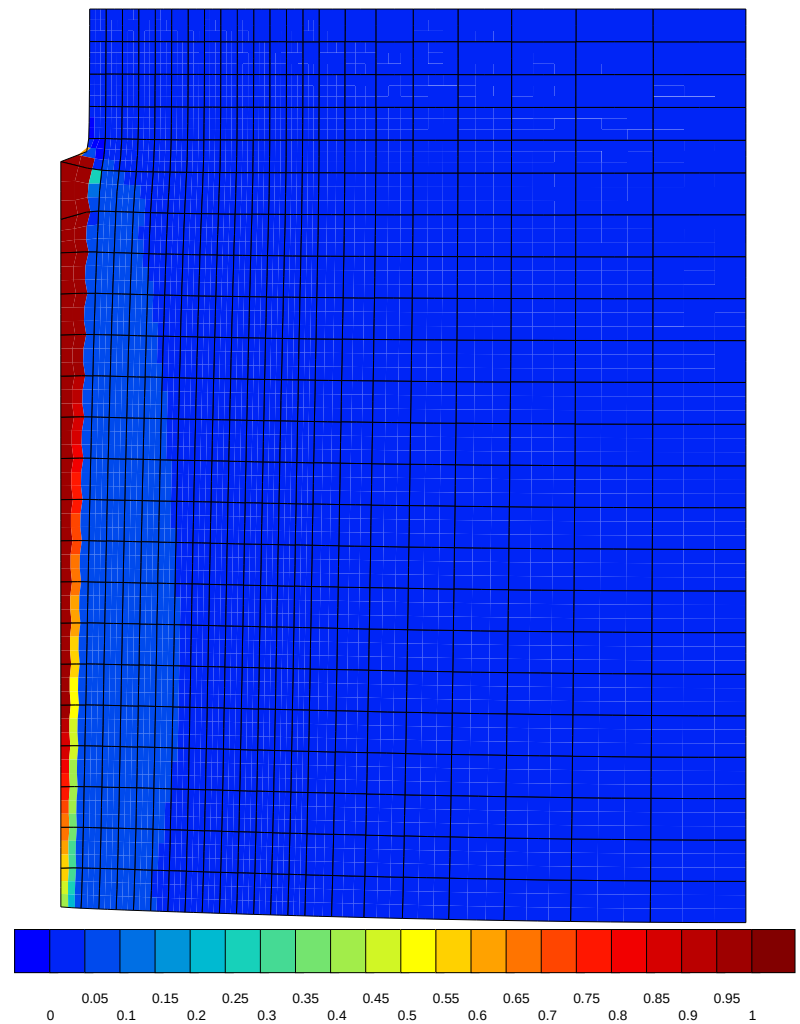




crack length : 10 mm

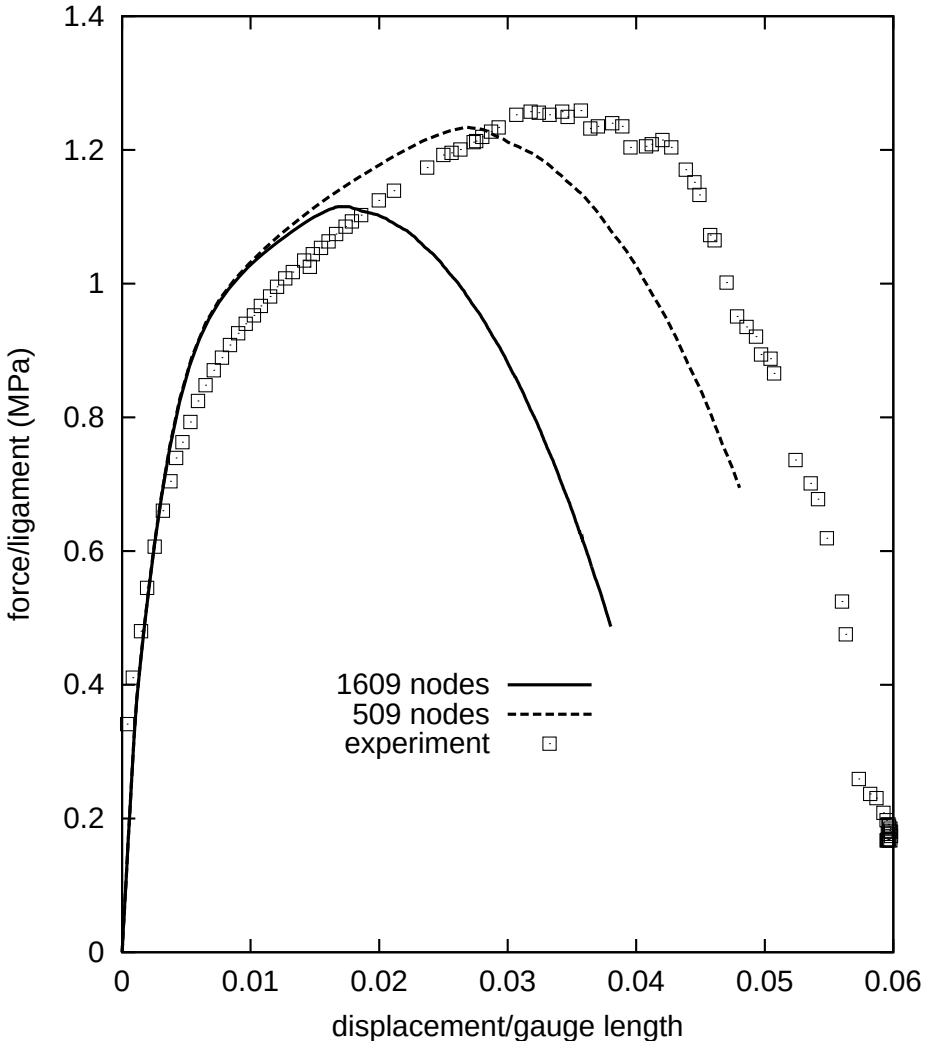
Tension of a cracked plate : Simulation within classical plasticity

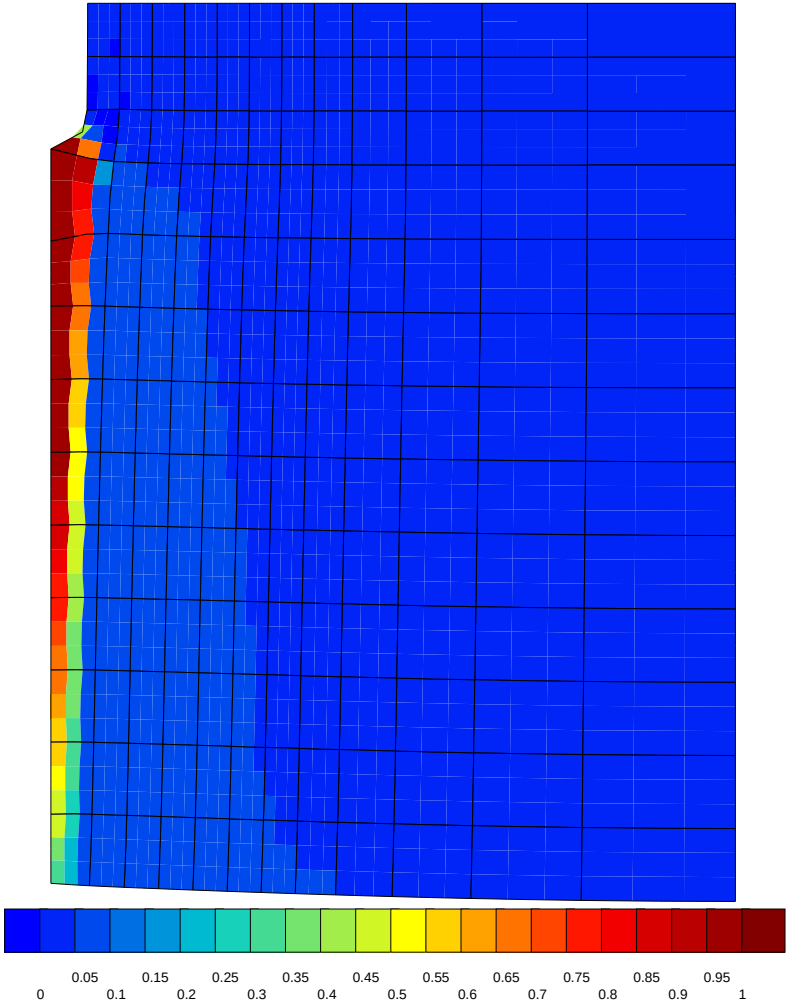




strain component ε_{11}

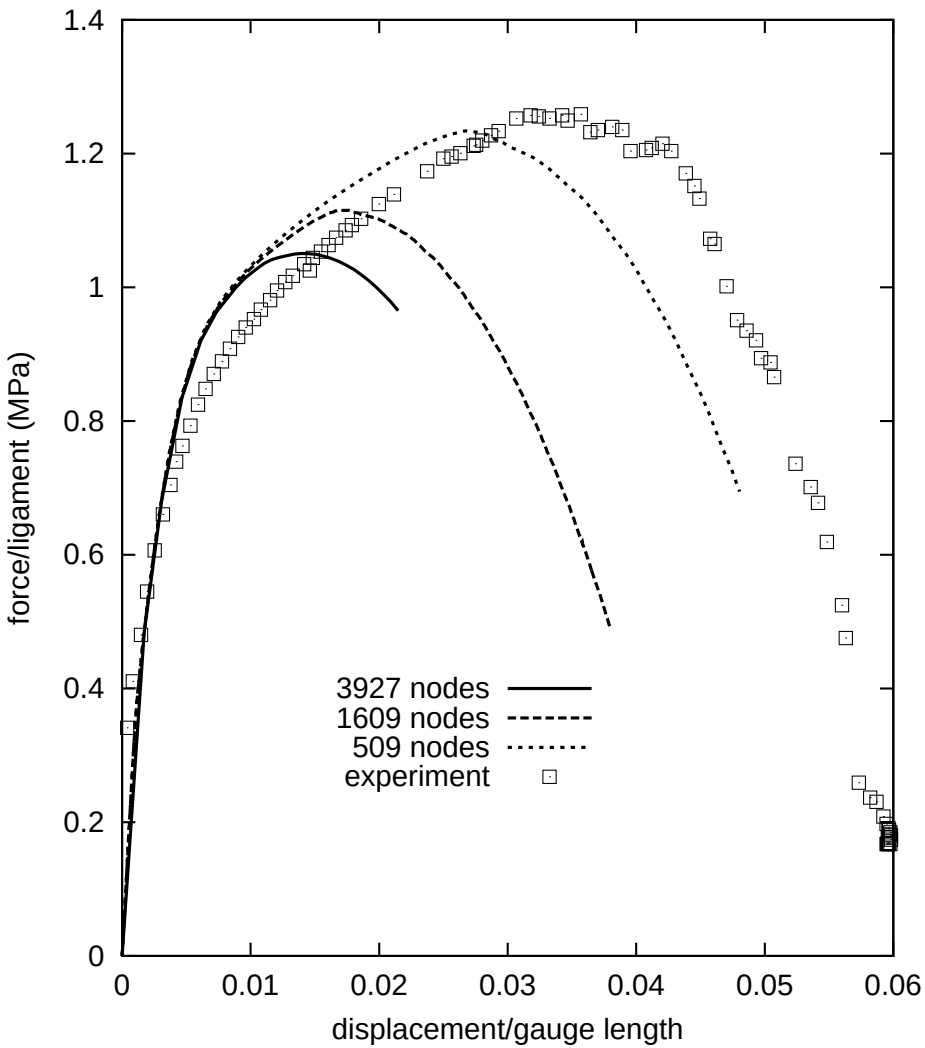
Tension of a cracked plate : Simulation within classical plasticity

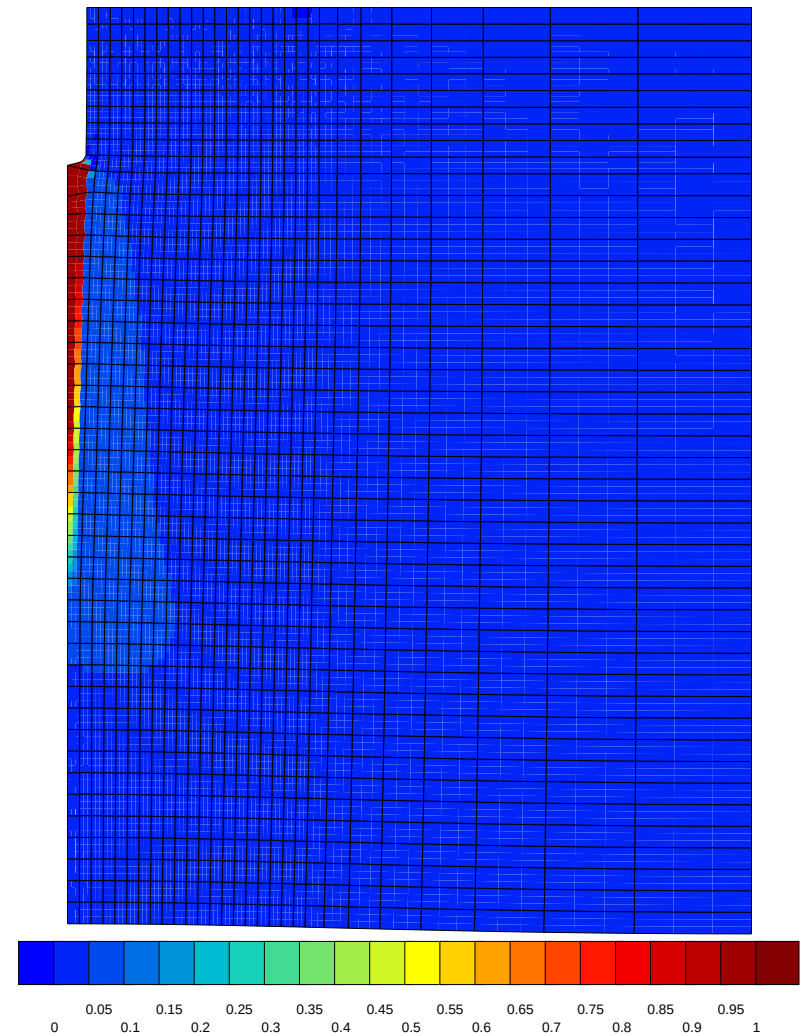




strain component ε_{11}

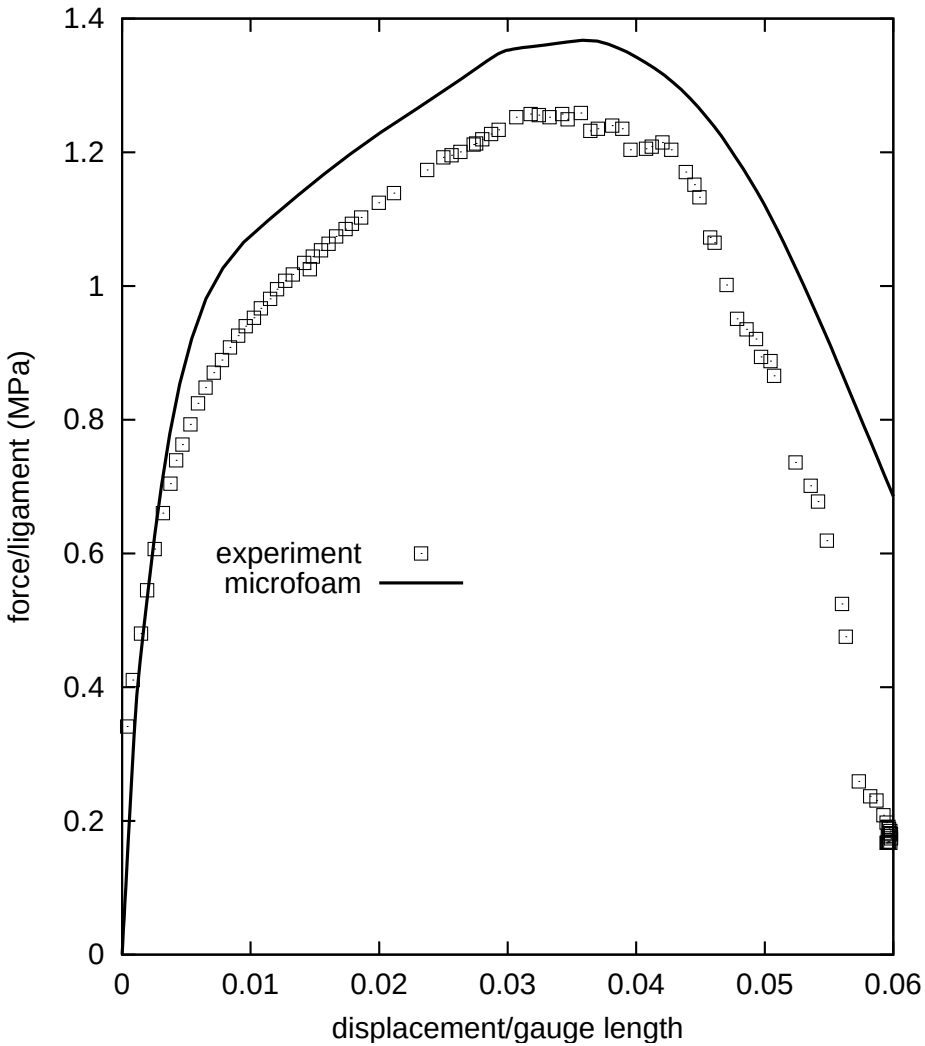
Tension of a cracked plate : Simulation within classical plasticity

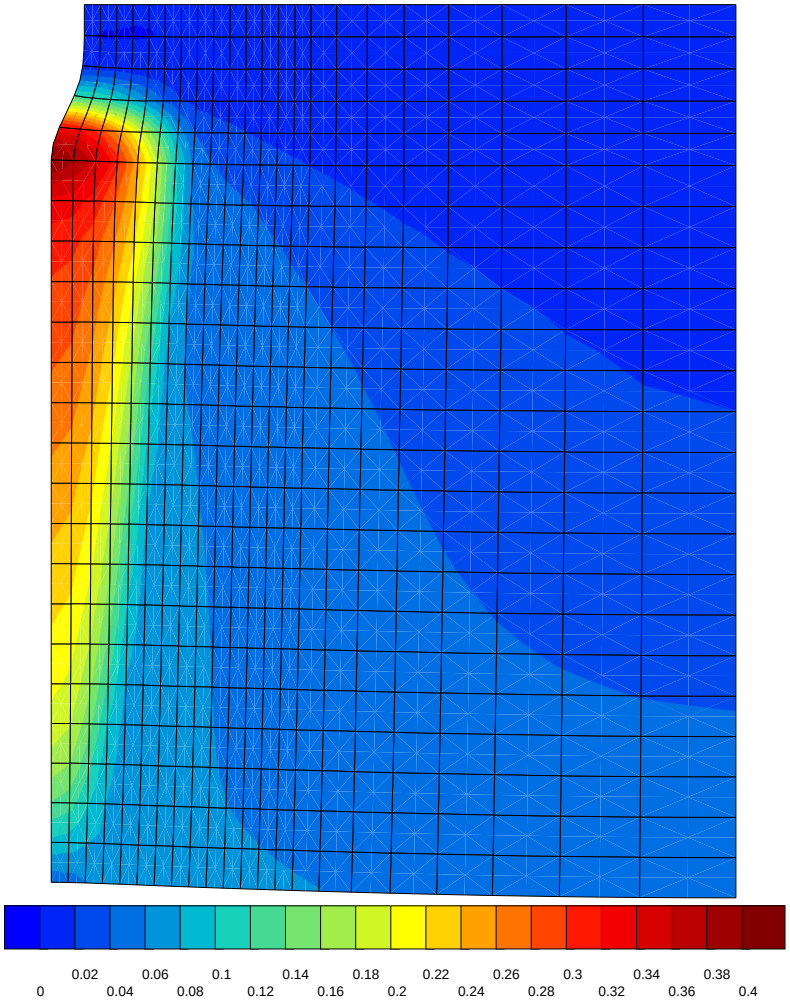




strain component ε_{11}

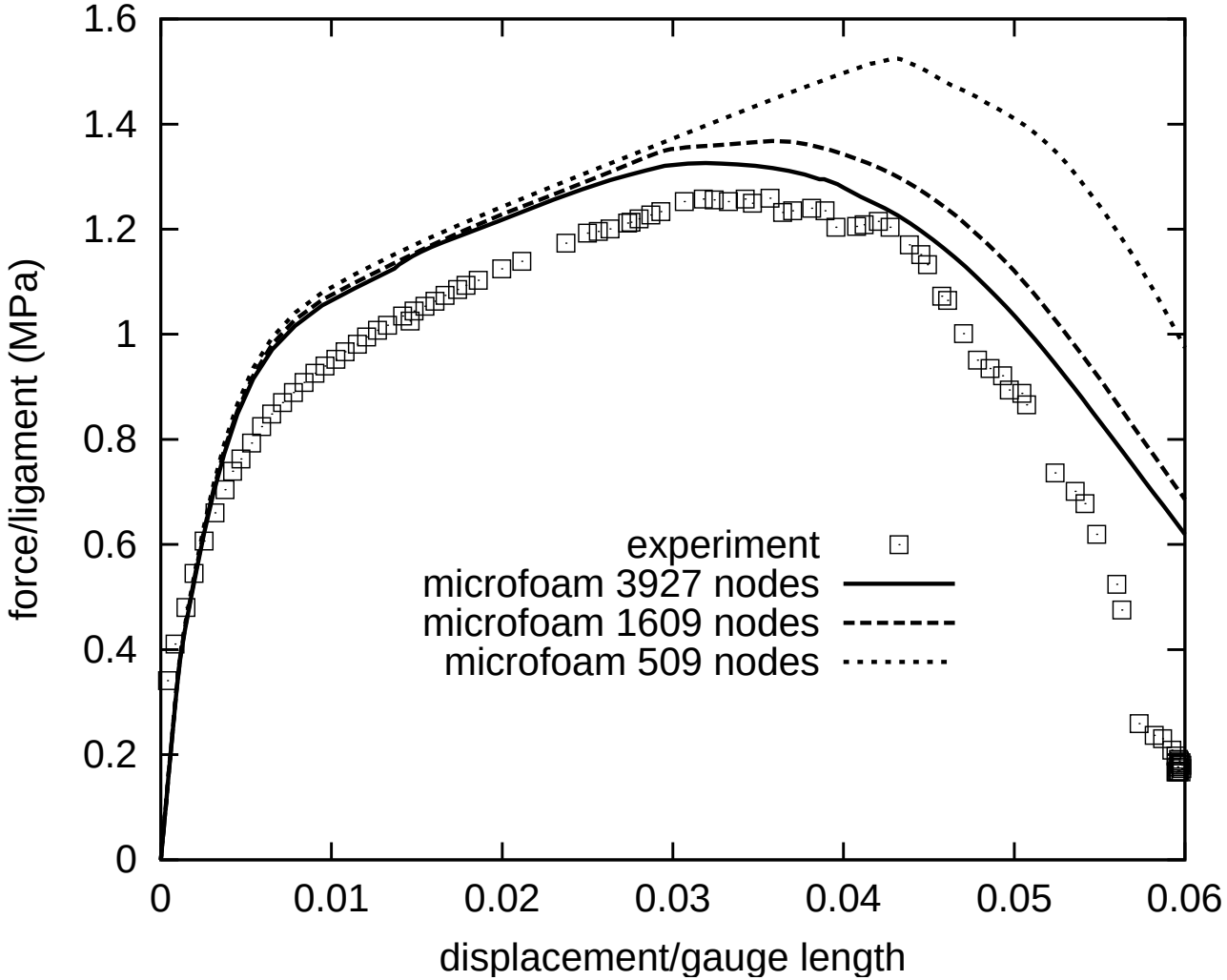
Tension of a cracked plate : Simulation with the *microfoam* model





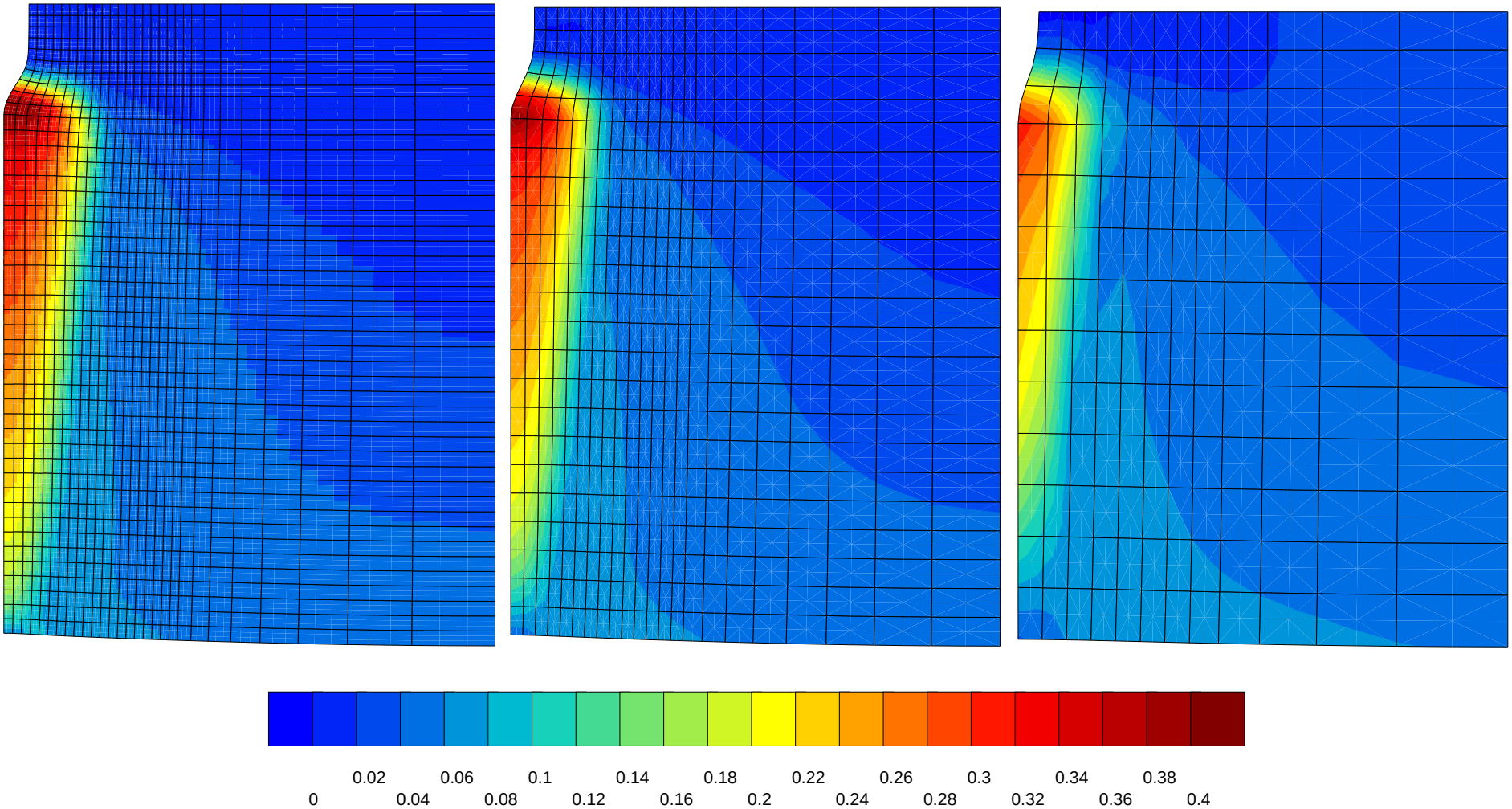
strain component ε_{11}

Tension of a cracked plate : Simulation with the *microfoam* model



influence of mesh size on the overall curves

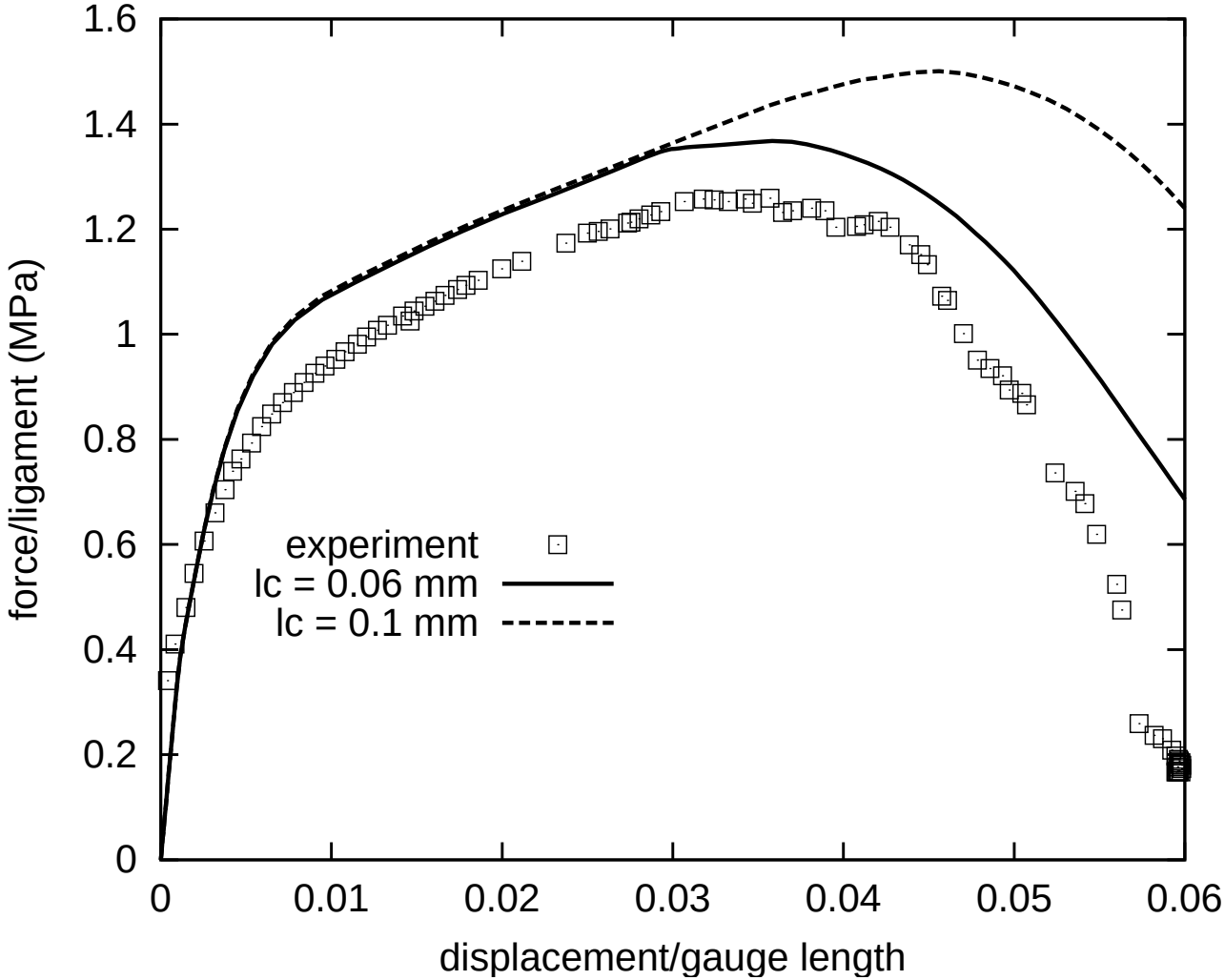
Tension of a cracked plate : Simulation with the *microfoam* model



influence of mesh size on the local field ε_{11}

23562 dofs 9654 dofs 3054 dofs

Tension of a cracked plate : Simulation with the *microfoam* model

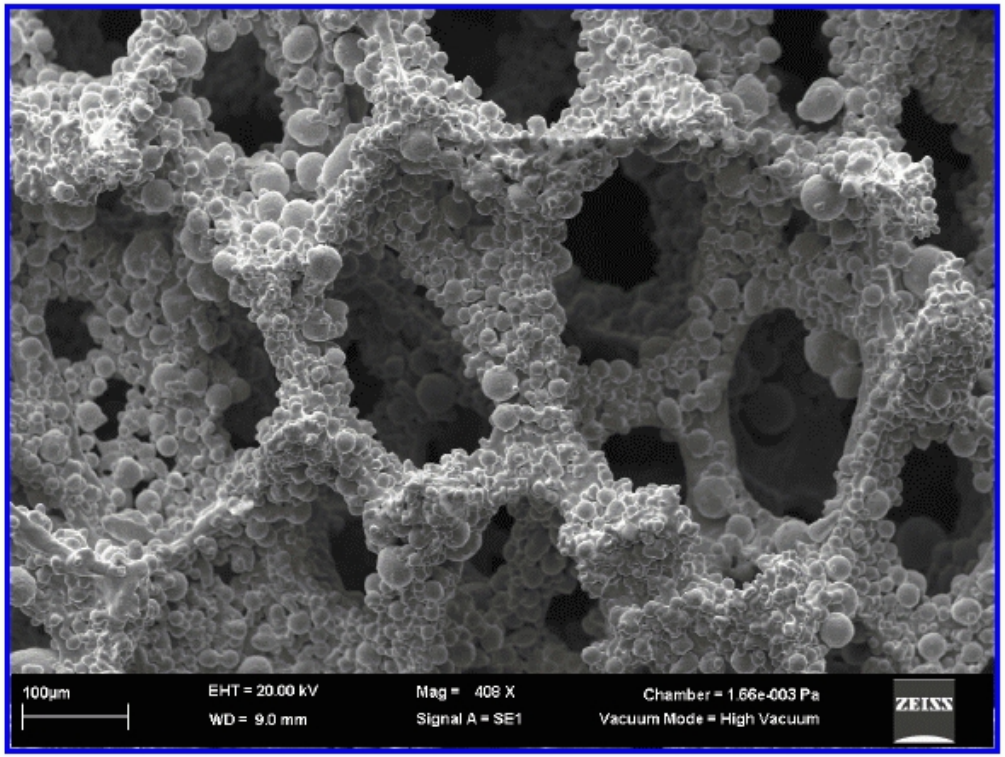


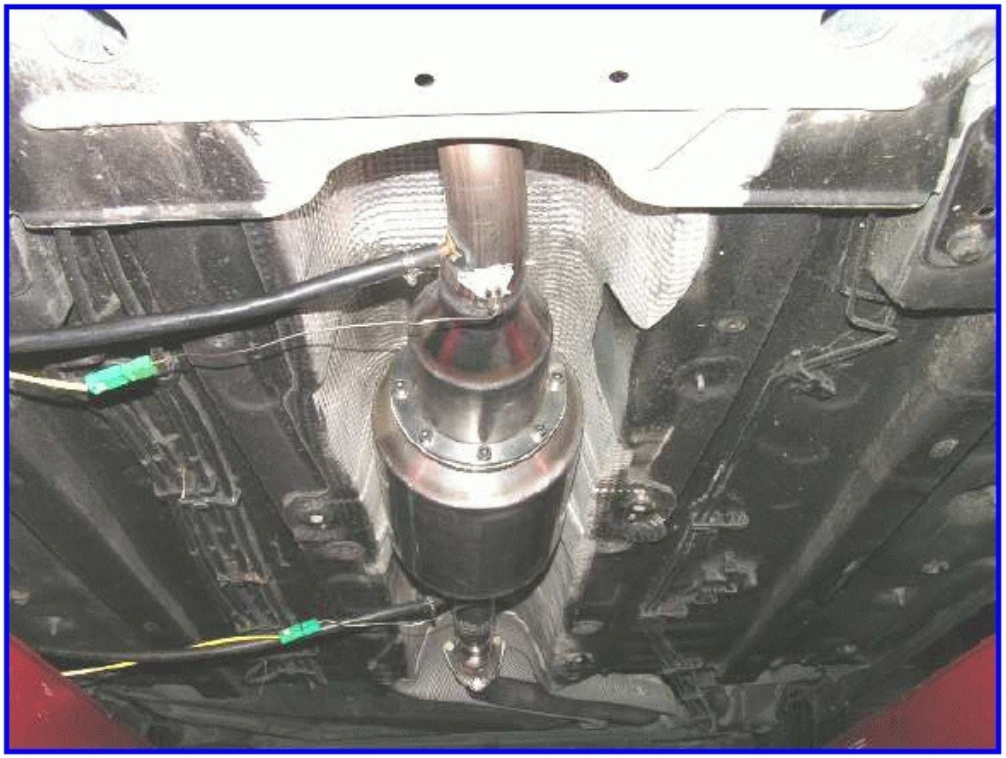
influence of the characteristic length on fracture : $l_c^2 = a_8/\mu$ with $\mu = 166.7$ MPa

New applications of open–cell foams

alloyed foams :

nickel base superalloy foams for DPF applications



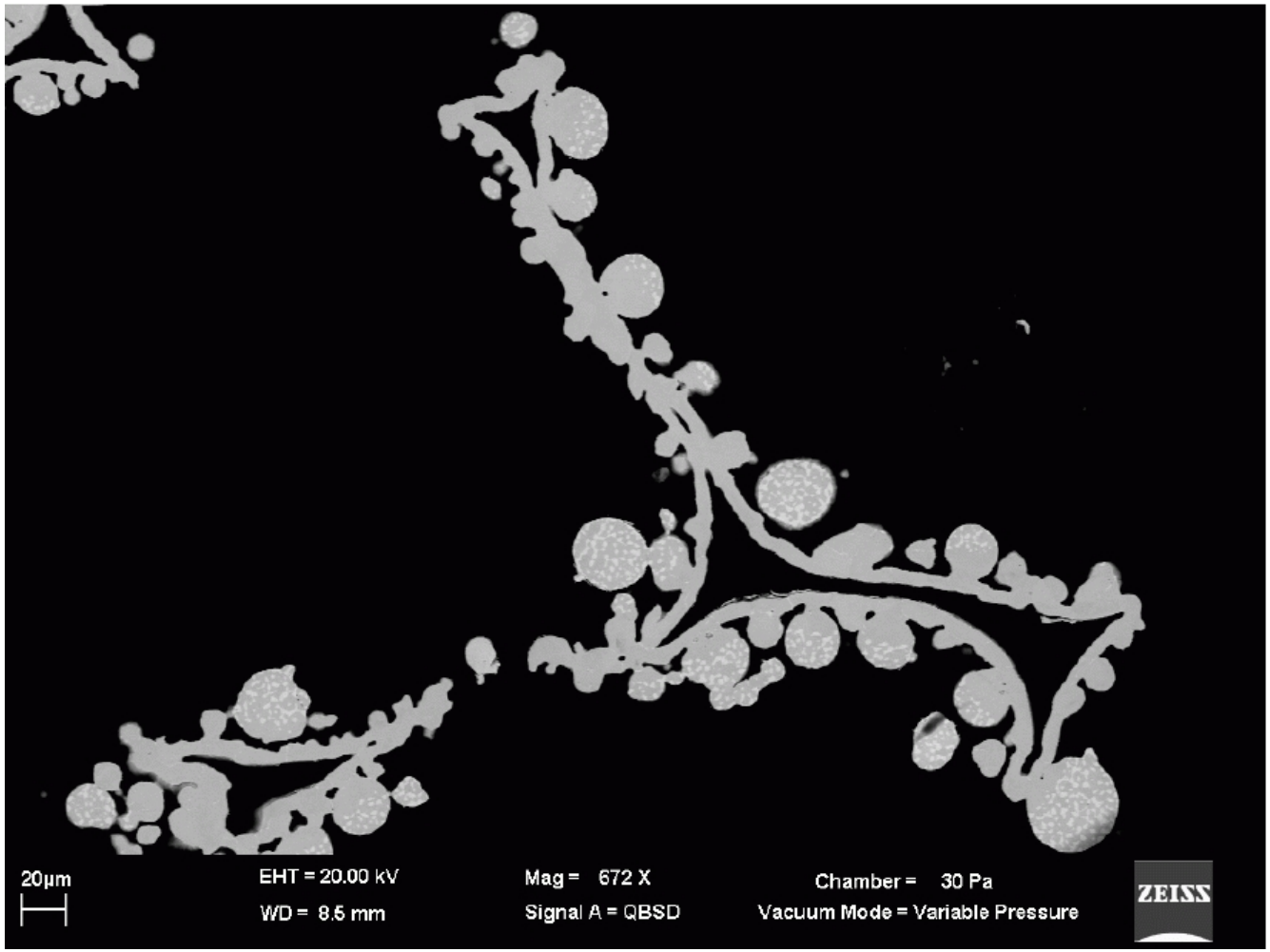


(cooperation Mines de Paris / IFAM Dresden)

New applications of open–cell foams

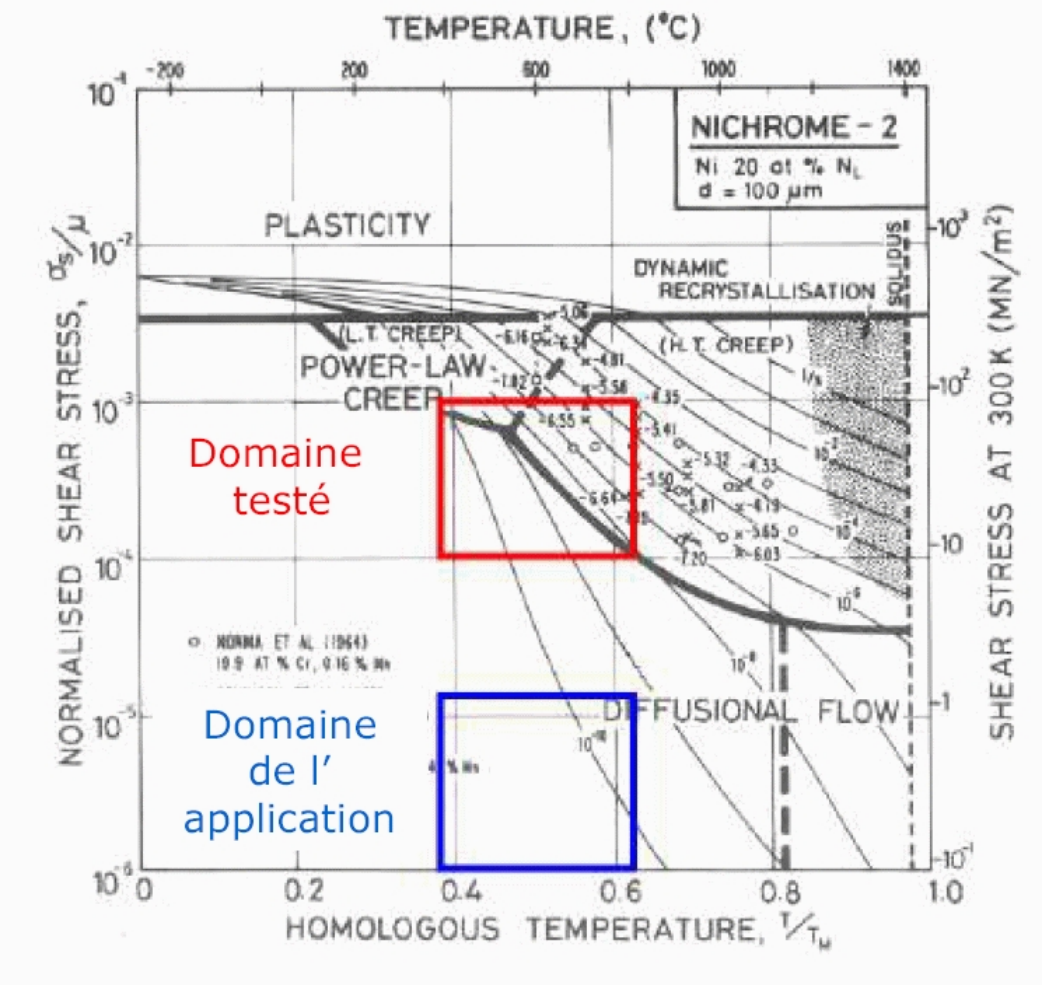
alloyed foams :

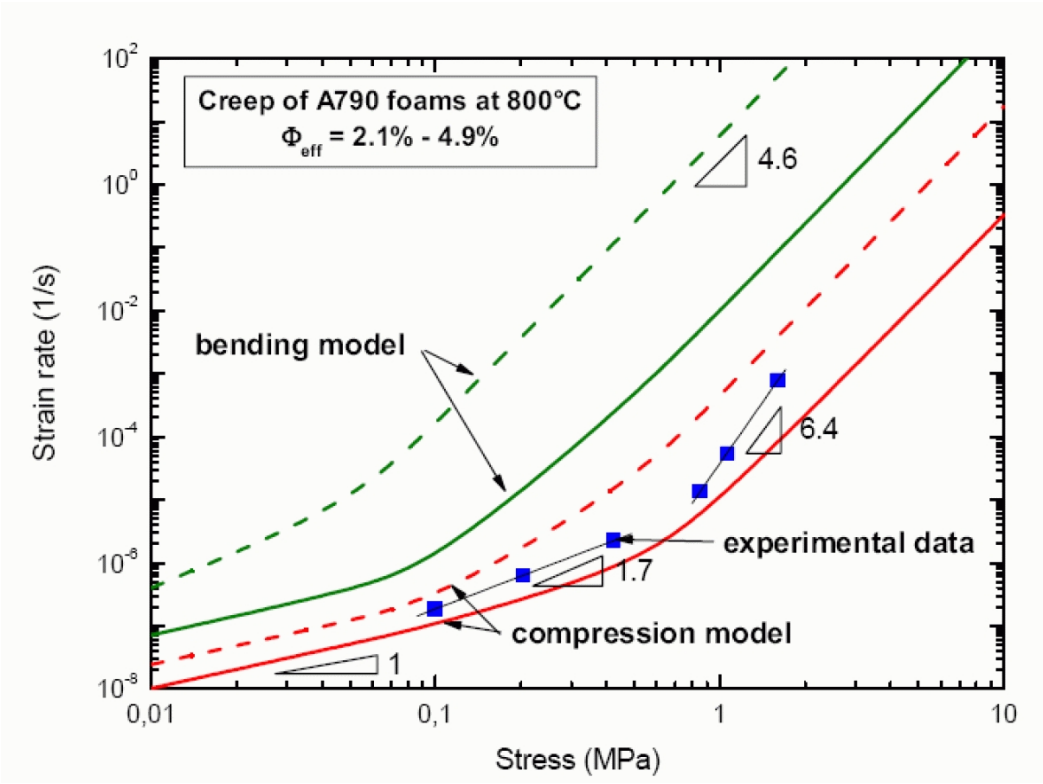
nickel base superalloy foams for DPF applications



(cooperation Mines de Paris / IFAM Dresden)

Creep of nickel and alloyed foams





Microstructural mechanics of nickel foams